Lightning & Trees:
Understanding Generation & Strike Probability

Dr. Kim D. Coder, Professor of Tree Biology & Health Care
Warnell School of Forestry & Natural Resources
University of Georgia (11/2013)

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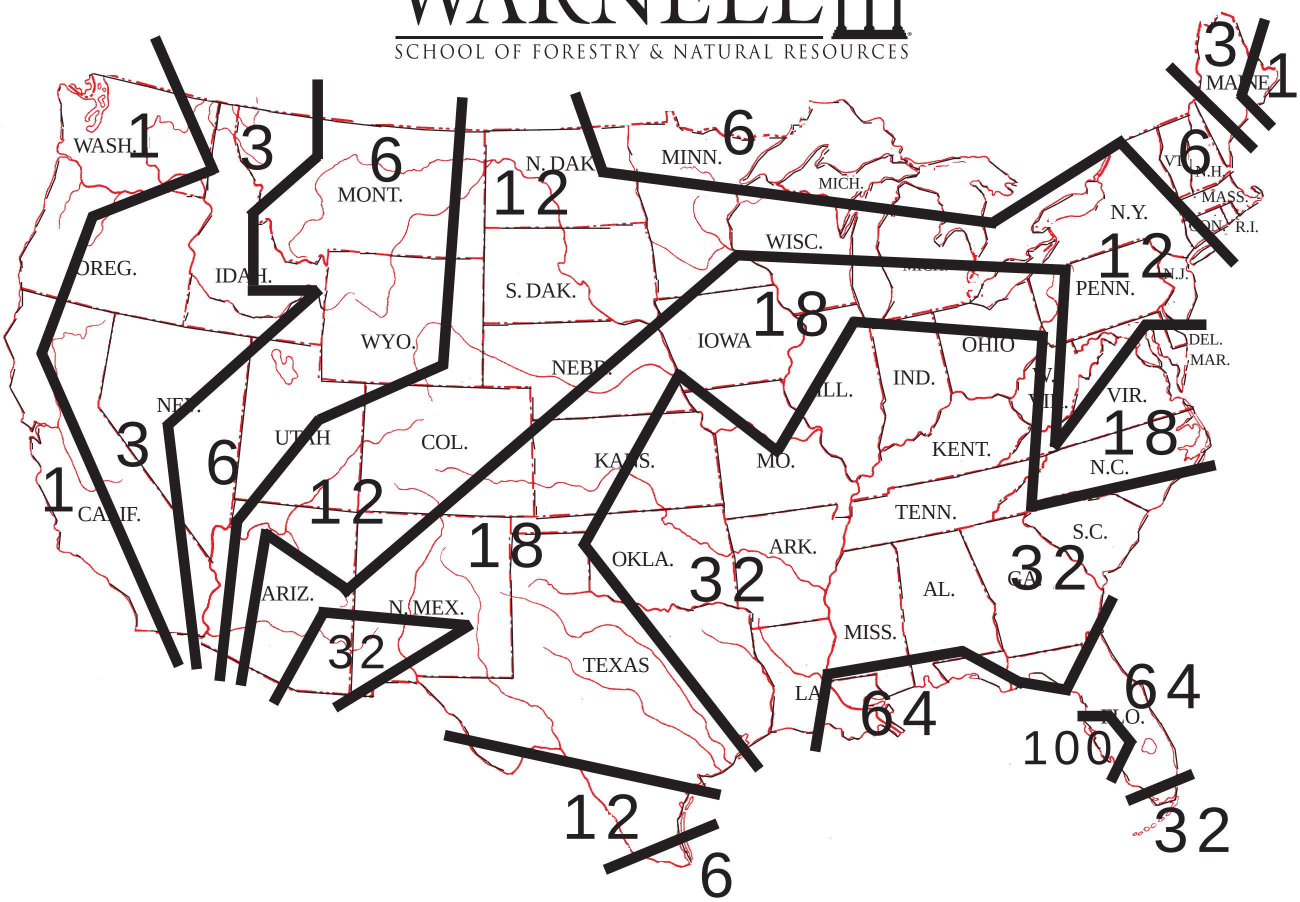

One source's proportional number of annual lightning ground strikes for continental United States compared with Tampa Bay area of Florida having the most at 100%.

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Lightning & Trees:

Understanding Generation & Strike Probability

by Dr. Kim D. Coder, Professor of Tree Biology & Health Care, Warnell School, University of Georgia

Lightning and trees share a mythological association centered around forces of nature. Lightning strikes, thunder rolls, and trees stand (or fall) over many years. Tree damage from severe lightning strikes can be massive and terminal. Even small damage volumes can be susceptible to attack by secondary pests, like bark beetles, leading to tree death. Dehydration, tissue disruption, heating, and bark loss can all initiate critical problems in trees.

This manual was designed to introduce lightning formation, strike attributes, and ground attachment as they impact trees. This manual does not present international, national or state tree lightning conduction and tree protection standards and practices, but research based information.

What Is Lightning?

Lightning is an extremely long electrical spark greater than 0.6 mile. Average lightning length is between 3-6 miles, depending upon global location and storm energy. Maximum length is about 60 miles. (Uman 2008). Lightning is the result of electrical charge separation by particle collisions in storm clouds areas with temperatures between 14°F and -4°F in the presence of super-cooled water. (Uman 2008)

Sparks generated by other means are not considered true lightning. Volcanic eruptions cause atypical lightning sparks generated from violent ash interactions. Nuclear ground and air bursts can also generate atypical lightning. (Uman 2008). Short sparks generated in laboratories (<10 feet) or in sand storms (<8 feet) are not considered lightning. Static electricity discharge from socks rubbed over a carpet generating <10,000 volts with spark length <0.15 inches is also not considered lightning. (Uman 2008).

How Much

There are ~2,000 active thunderstorms per day worldwide. Lightning strikes ground somewhere on Earth 9 million times a day -- 6,200 times a minute -- 100 times per second. (Uman 2008) Lightning ground strikes for a typical small thunderstorm averages about 1 strike every 30 seconds for roughly 50 minutes over a ground area of 80 square miles. Figure 1 shows the world's top five recording stations for cloud to ground strikes per year per square mile. (Bouquegneau & Rakov 2010).

One estimate is 500,000 lightning strikes terminate on trees every day (~6% of all lightning strikes). Lightning severely damages and kills thousands of trees each year. Many of these trees line community streets, stand in parks, and surround homes and schools. Figure 2 provides a list of cloud to ground lightning strikes per square mile per year for states with the most and least strikes.

For example, Georgia has between 50-70 thunderstorm days per year. These thunderstorm events annually generate an average of 15 lightning ground strikes across every square mile in Georgia. Over a number of years, storms will produce many lightning ground strikes which cause extensive damage to historic, rare, specimen, and valuable trees. Tree health care providers need to understand lightning forces, damage, treatment, and protection.

Damage Costs

The cost of lightning damage is large. In one study in Canada, Mills and his team found around $1 billion per year are lost in the largest four sectors of the economy plagued by lightning. These sectors are human

rank #	world location	annual lightning strikes per square mile
1.	Kamembe, Rwanda	215
2.	Boende, Congo	172
3.	Lusambo, Congo	135
4.	Kananga, Congo	130
5.	Kuala Lumpar, Malaysia	125
	Tampa Bay, Florida (highest lightning strikes in US)	42

Figure 1: Top five places on Earth with the highest recored cloud to ground lightning strikes per year per square mile.
(Bouquegneau & Rakov 2010)

rank	state	lightning strikes per year per square mile
1.	Florida	33.1
2.	Oklahoma	32,7
3.	Arkansas	29.2
4.	Missouri	27.3
5.	Indiana	27.0
5.	Kansas	27.0
6.	Louisiana	26.6
7.	Illinois	25.3
8.	Iowa	25.2
9.	Mississippi	24.9
12.	Georgia	22.1
45.	Idaho	2.2
46.	Rhode Island	1.8
47.	Oregon	1.3
48.	California	1.1
49.	Washington	0.4

Figure 2: State rankings of average annual cloud to ground lightning strikes per square mile. (2005-2009 USPLN data)

health, property damage, forestry impacts (fire centered), and damage to the electric grid. Data is either poor or missing in several other sectors of the economy concerning lightning (i.e. aviation). Figure 3 provides the break down by sectors for lightning damage. In the United States, average annual loss from lightning is cited as roughly $5 billion, $2 billion just from aviation sector alone not including $200 million cost in military aircraft per year. Approximately 30% of all power outages in the United States is lightning related accounting for $1 billion in costs. Annual insurance costs from lightning are given in Figure 4. (Uman 2008).

Human Health

Lightning has an important impact on human health. Lightning both injures and kills many people each year in the United States. About 500 people are seriously injured each year from lightning -- of these people, approximately 100 (20%) are killed. Feed lot and pastured animal losses are significant. Direct property damage has been estimated to be $175 million annually in the Southern United States. Damage to utility structures is immense. Both forest trees and trees along community streets and in yards are severely damaged.

Fatality data from lightning is given in Figure 5. This figure shows average deaths from storm events in the United states per year. Of the four major categories of storm fatalities -- flood, lightning, tornadoes, and hurricanes -- lightning is responsible for 27% of all deaths. Figure 6 provides a 10 year distribution of lightning caused death by location or activity. Hiding under, or in contact with, trees comprises 19% of all lightning fatalities. It is clear to stay out of the open and from under trees, and do not boat, farm, or golf, under impending lightning generating conditions.

Figure 7 shows lightning deaths rankings by state per year. Injury to people (and domestic animals) is not just from being along the direct current path of a cloud to ground strike. People can be injured from:

1. being in the direct current path and ground arcing area;
2. standing in the step voltage area
3. touch voltage (contact with objects along energized path);
4. side flash away from direct current path; and,
5. being a part of a ground streamer path not eventually connected to direct lightning path.

The electric field changes surrounding a lightning pathway can initiate many types of injury because of the massive field strength, and the electric filed needed to impact humans physically and biologically can be so small. Figure 8 shows the top medical injuries and associated problems demonstrated by lightning strike survivors.

T-Storms

Lightning formation requires great energy transformations. These lightning generators are thunderstorms. Thunderstorms can be found across the continent. Thunderstorms generate updrafts in the atmosphere, large columns of falling rain and air, and ground level winds. The straight line winds in a thunderstorm can be caused by downbursts of various sizes: microbursts (<1 mile diameter & 160 mph winds); macrobursts (>2.5 miles diameter & 130 mph winds); and, derechos (band of downburst clusters >240 miles long & >100 mph winds). Hot, humid air running into colder air masses tend to generate storms with massive, energetic air flows.

Figure 9 shows a historic map of annual thunderstorm days recorded in the United States over a 30 year period. Figure 10 shows a current map of thunderstorm day averages per year. Figure 11 provides a map of thunderstorm days per year averaged over the 1990's. Note the general trend for increased thunderstorms days as you travel South and East in the United States. The Tampa Bay area of Western Florida is the storm capital of the United States.

HEALTH
10 deaths
164 injuries
(20% to hospital)
$79.2M injuries / fatalities

PROPERTY
$23.5M insurance claims
$16.4M fires

FORESTRY
$438M fires

ELECTRIC GRID
$445M outages
$16M lost revenue

TOTAL = ~$1B

Figure 3: Annual lightning related losses in the largest four economic sectors in Canada. (Mills et.al. 2010)

Insurance Costs / Losses From Lightning

5% of all claims have lightning related damage (~$660 million)

average pay-out per lightning ground strike = $12.00

1 lightning related damage pay-out per 60 strikes

EXAMPLE DAMAGE / LOSS:

- house fires =
  - $175 million/year
  - 30,000/year
- 30% of all church fires
- 10,000 wildland fires in Western US
- primary cause of farm / ranch fires
- 80% of all livestock losses
- $100 million computer / electronics

Figure 4: Annual lightning related losses in the United States from the insurance sector of the economy. (Uman 2008)

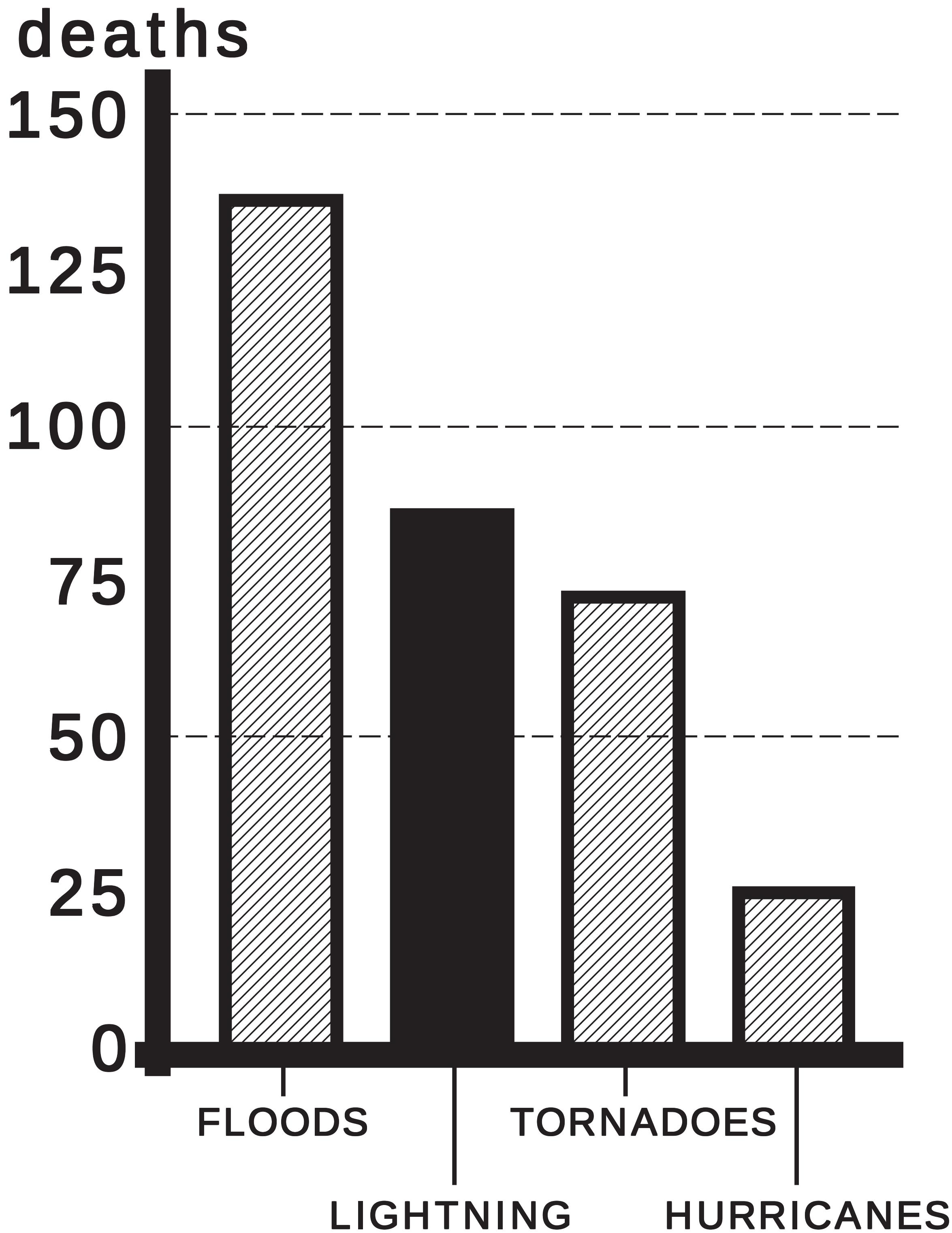


Figure 5: Average number of storm related deaths per year in the United States. (NOAA data from Rakov & Uman 2003)

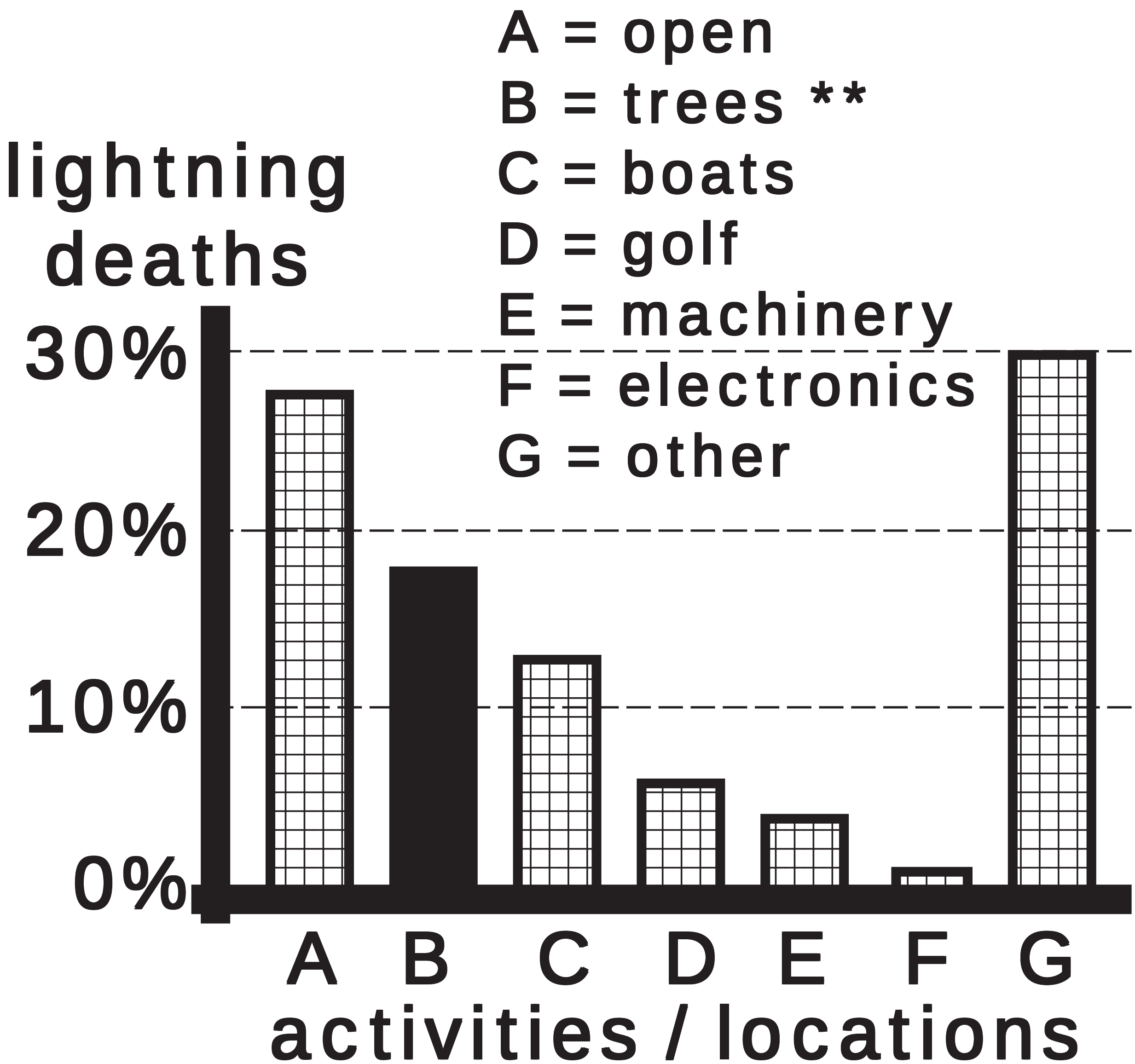


Figure 6: Lightning deaths for a 10 year period in the United States by location or activity.
(NOAA data listed in Rakov & Uman 2003)

rank	state	annual deaths	deaths per million
1.	Florida	7.4	0.43
2.	Texas	2.8	0.12
3.	Colorado	2.7	0.59
4.	Georgia	2.3	0.26
5.	North Carolina	1.9	0.22

Figure 7: Top five state rankings for average lightning fatalities, and deaths per million people in each state. (1998-2007 data)

top medical problems	percent of lightning survivors
memory problems	52%
sleep disorders	44%
attention deficits	41%
dizzy	38%
fatique	37%
numbness / paralysis	36%
joint stiffness	35%

Figure 8: Percent of lightning strike survivors claiming specific medical problems.

THUNDERSTORM DAYS

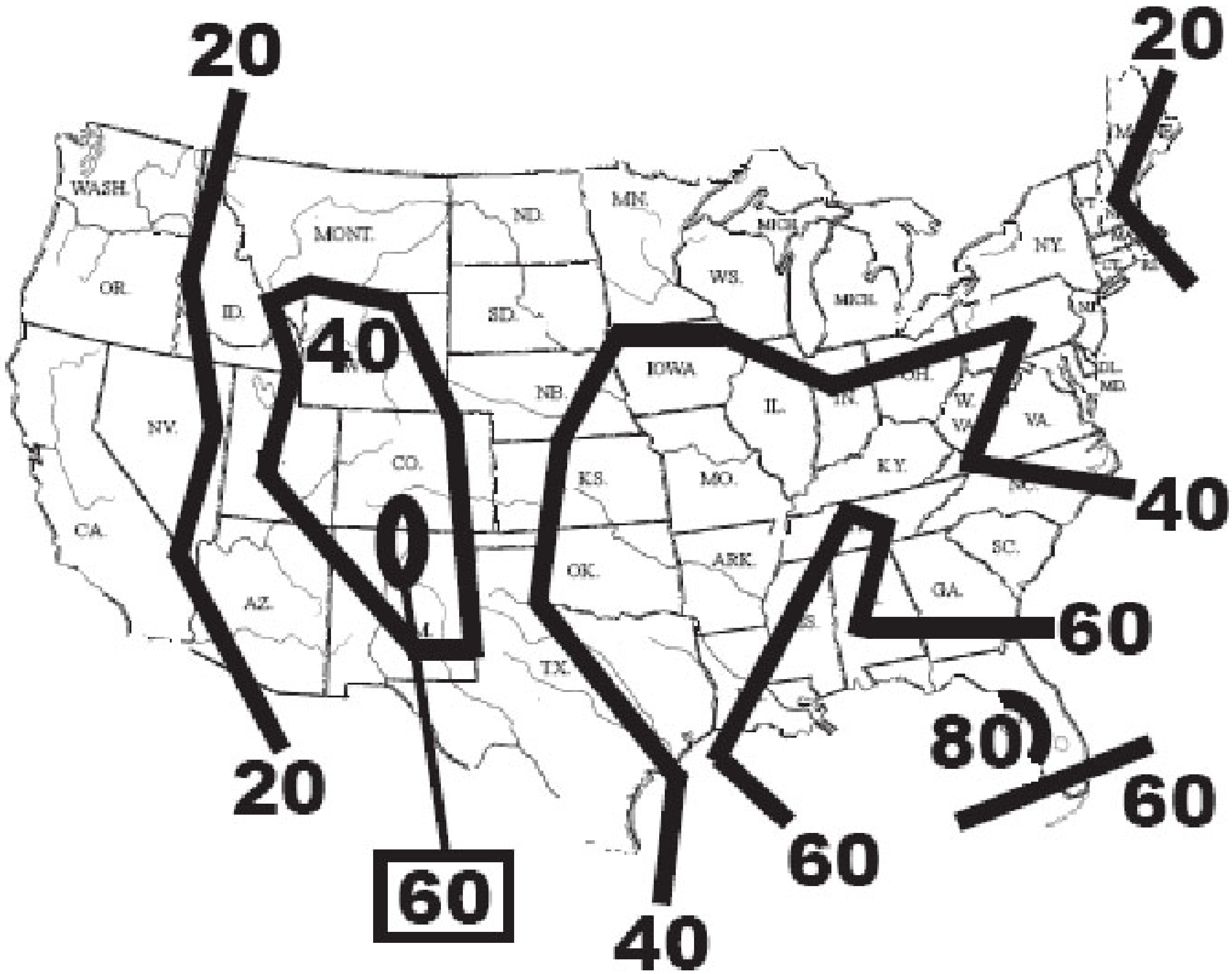


Figure 9: Average thunderstorm days per year.
(30 year national summary -- NOAA)

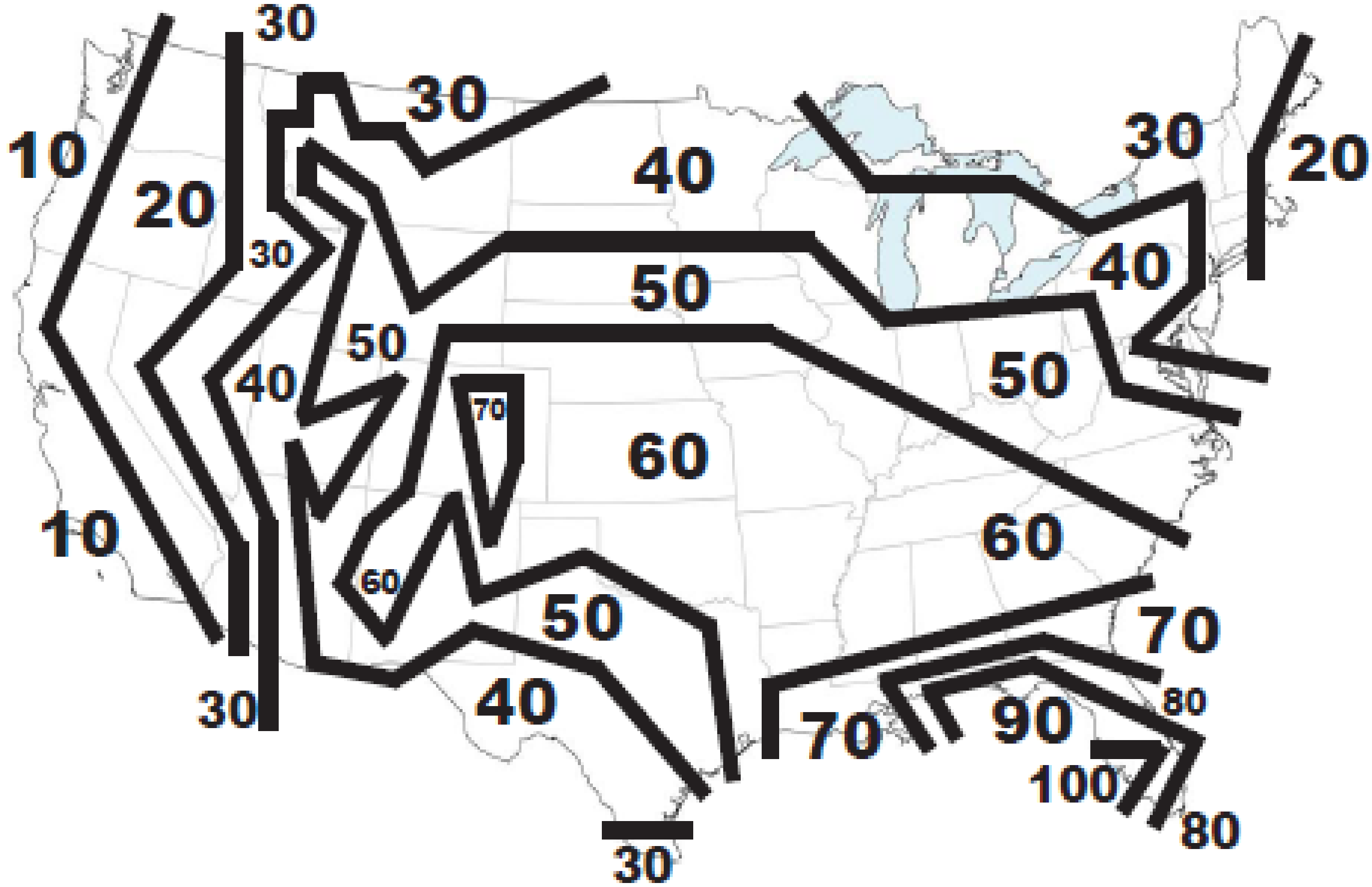


Figure 10: Average thunderstorm days per year.

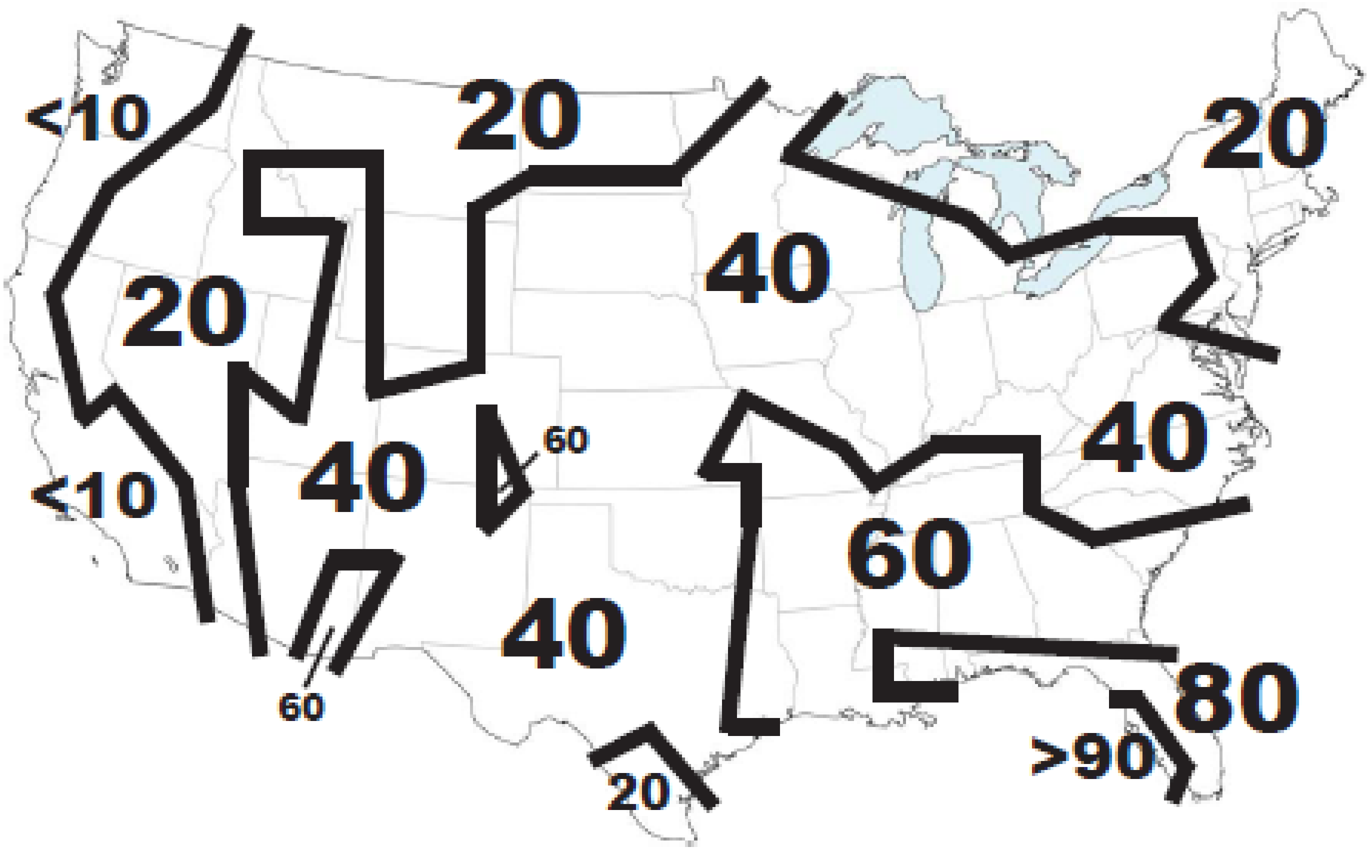


Figure 11: Average thunderstorm days per year. (national 1990-1999 data)

Storming On

Within thunderstorms, intense updrafts occur spinning up into tornadoes. Tornado events are on the rise in the United States. Since 1950, tornado events have increased roughly seven-hundred percent (7X). Figure 12 shows tornado numbers over the last 55 years. Tornadoes generate intense lightning discharges. Figure 13 provides a map of average number of tornadoes per year expected. The map categories are broad but demonstrate a concentration of storms in the legendary "tornado alley" of the Great Plains. Separating tornado initiated and general thunderstorm lightning events is not possible, except faster updrafts have the potential for greater charge generation and separation.

Storm Intensity Zones

In trying to summarize storms and lightning associated damage to trees, the Coder Storm Intensity Map was developed for the continental United States. This map was created using averages of historic data for thunderstorms, hurricanes, tornadoes, lightning ground strike frequency, ice glazing events, snow fall accumulation values, and general wind speed values. The result is shown in Figure 14, a map of storm intensity as it relates to potential tree damage.

The range of storm intensity impacting trees are categorized into zones from 0 to 10. The most intense area of potential tree damage from storms is in zone 10, the southern tip of Florida. Thunderstorm (hurricanes are series of thunderstorms), tornadoes, and lightning events were part of this composite cluster analysis. Note some area are dissimilar in climate and weather events but share similar total composite tree damaging environments.

Lightning Location

To arrive at actual lightning ground strikes per year, there are a number of equations using thunderstorm days per year. One general estimate of lightning ground strikes per year is multiplying thunderstorm days for an area times 0.2. (Uman 2008) A research formula is given in Figure 15. In this figure the number of lightning ground strikes per square mile per year is determined by using the number of thunderstorm days per year. This formula is modified using average values from multiple papers. Figure 16 provides another way to compare lightning ground strikes per square mile per year with annual thunderstorm days. These thunderstorm days formula are only for rough estimation of lightning strikes.

With improving technology, cloud to ground lightning strikes can be directly measured and mapped. Figure 17 is a simplified map of lightning ground strikes per square mile per year over a decade. Figure 18 provides ground strikes per square mile per year for the last 15 years. For example, using 40 lightning ground strikes per square mile per year means there is a 90% chance of a strike within 725 feet, 50% chance of a strike within 395 feet, and 10% chance of a strike within 165 feet of any point on the ground per square mile per year. (Uman 2008).

Comparing ground strike maps from many years suggest complex changes are occurring in number and location of lightning ground strikes. As global climatic changes increase average temperatures, a 2^{o}F increase in average temperature increases by 11% atmospheric energy and increases by 10% number of lightning strikes. (Bouquegneau & Rakov 2010).

Lightning Generation

Storms generate large updrafts and pull moisture laden air up to high, cold altitudes. Various types and sizes of precipitation form in storms. In the simplest terms, electric charge fields generate lightning are concentrated when tiny ice crystals and larger wet ice particles (graupel) collide. These collisions within storm updrafts leave electrical charges on small crystals and opposite charges on larger particles.

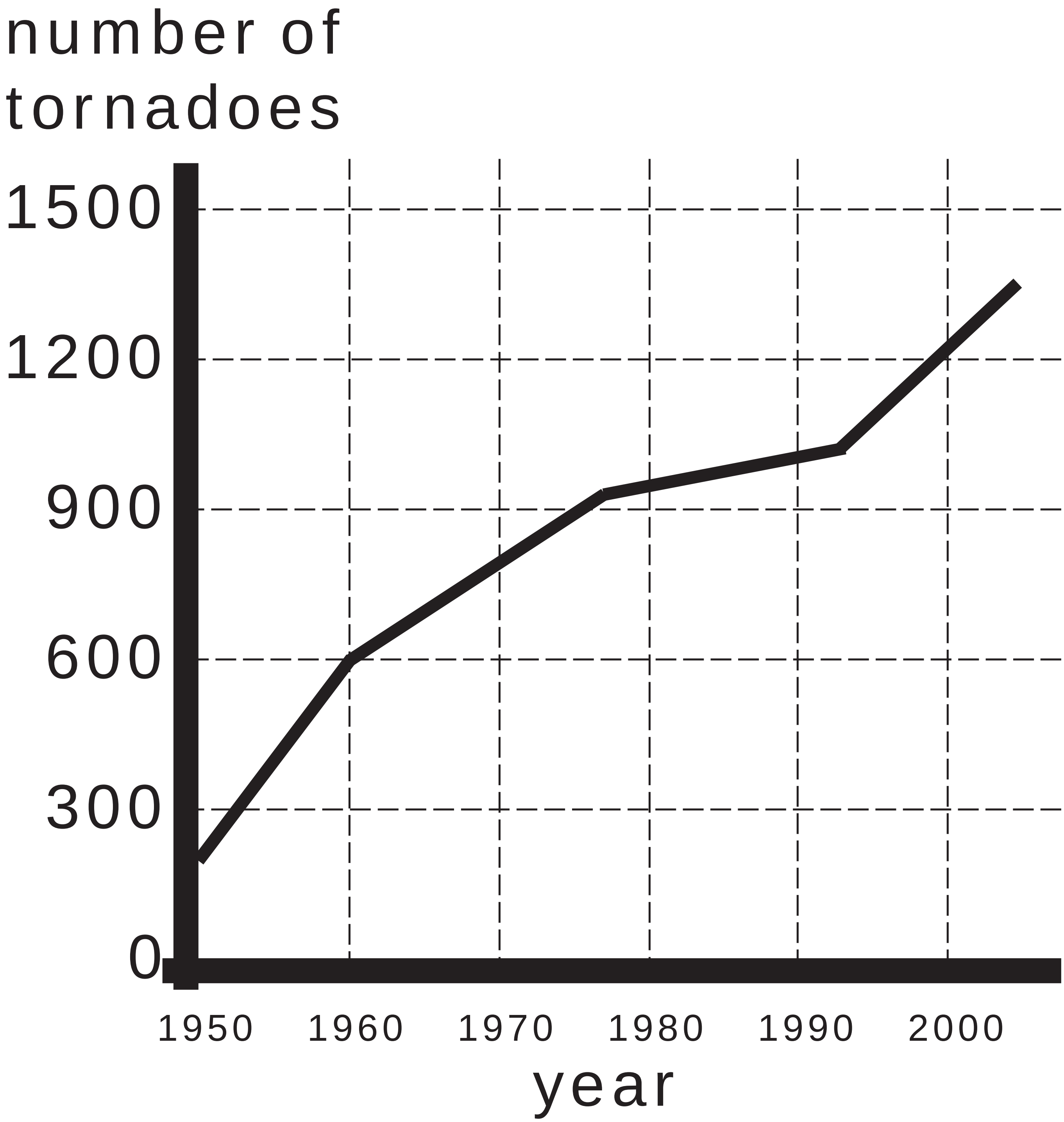


Figure 12: General trend line for tornado numbers in the United States over 55 years. (NOAA data)

TORNADOES

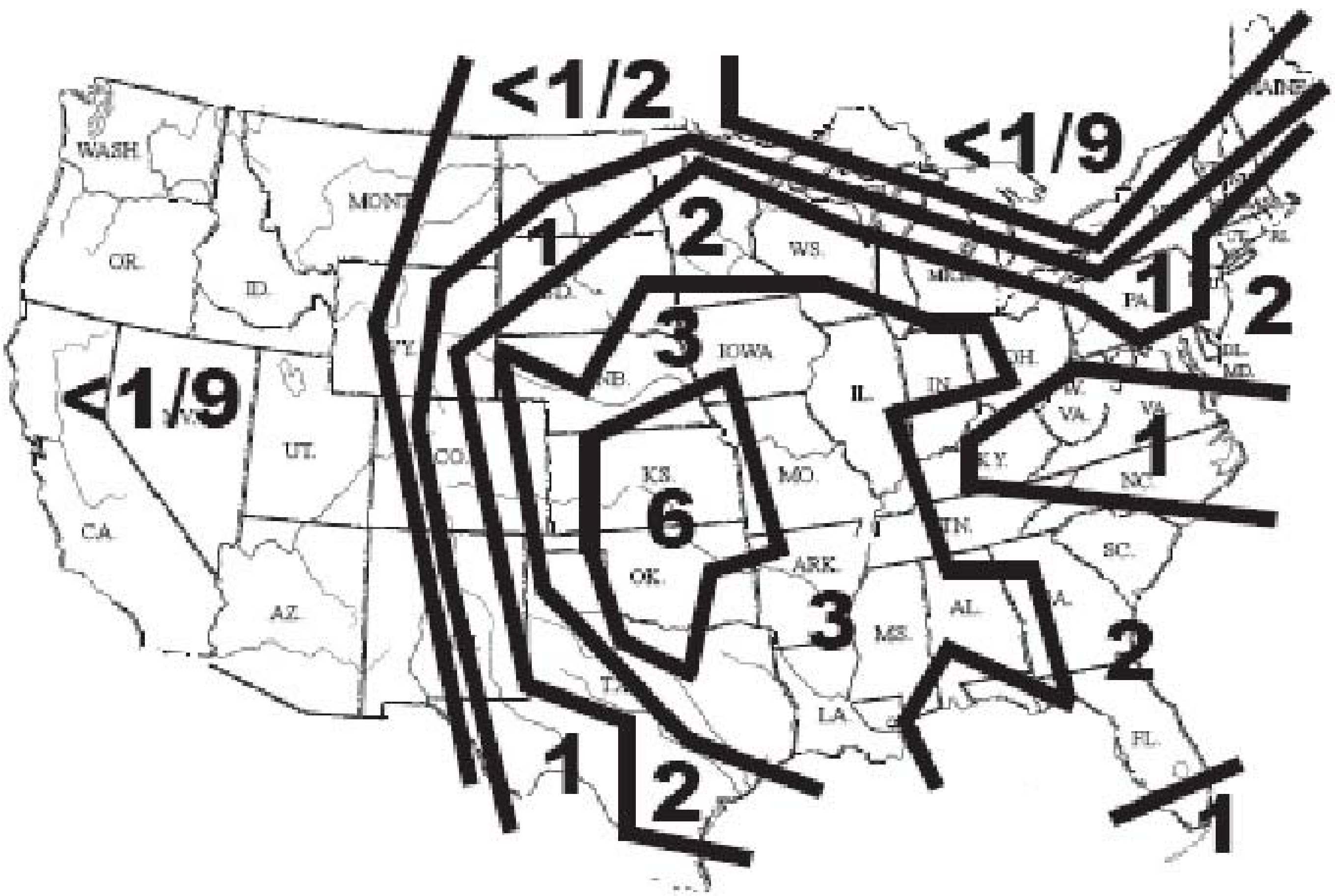


Figure 13: Average tornadoes per year. (45 year data -- NOAA)

TREE DAMAGE

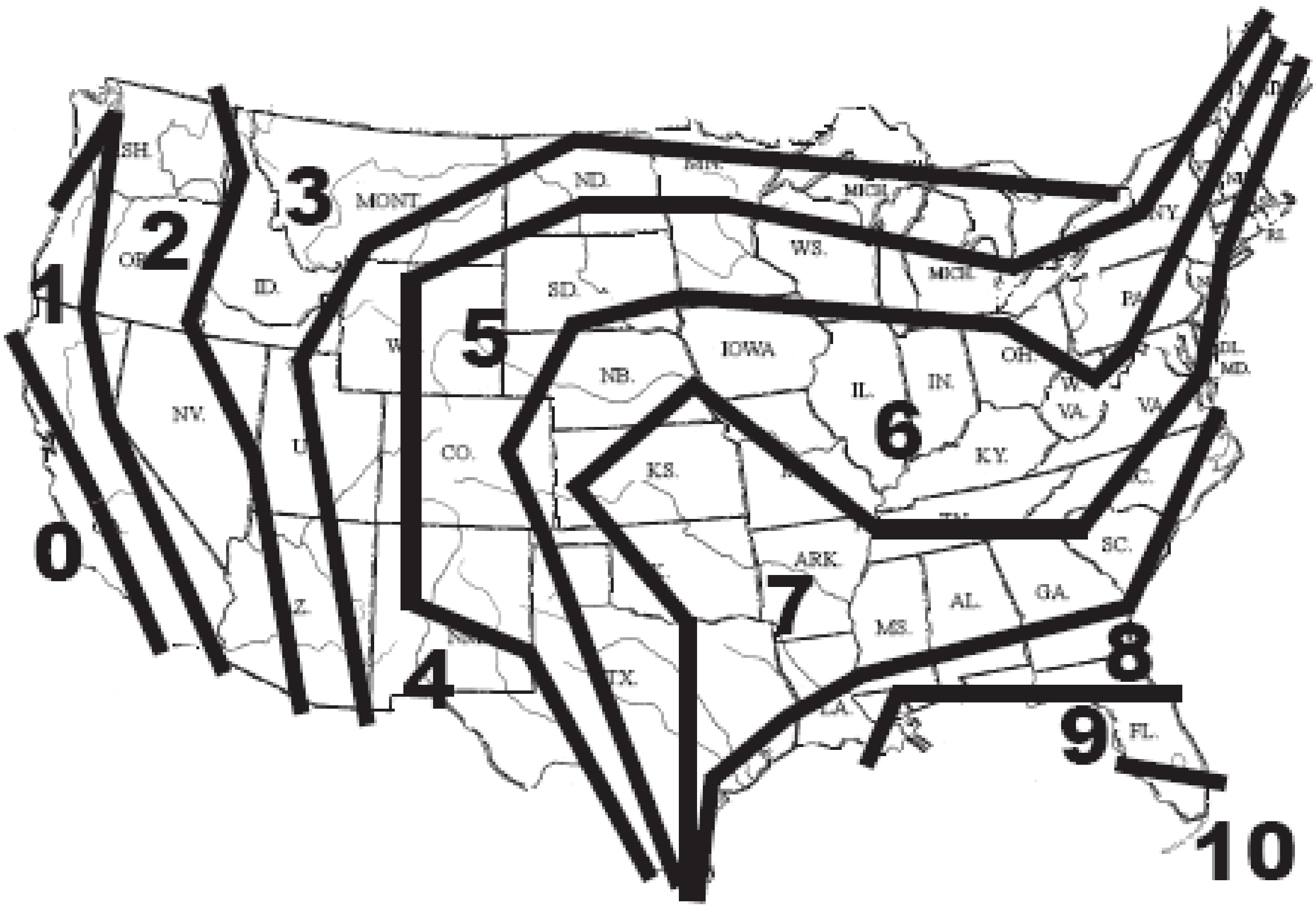


Figure 14: Coder composite storm damage intensity map for potential tree injury / damage, with lightning as one of the damaging components. (highest risk = 10; lowest risk = 0)

Number of Lightning Ground Strikes per square mile per year = N

Number of Thunderstorm Days per year = T

$$N = (0.015 \times (T)^{1.34}) \times 2.59$$

Figure 15: Estimating cloud to ground lightning strikes per square mile per year using thunderstorm days per year.
(after Cooray & Fernando 2010)

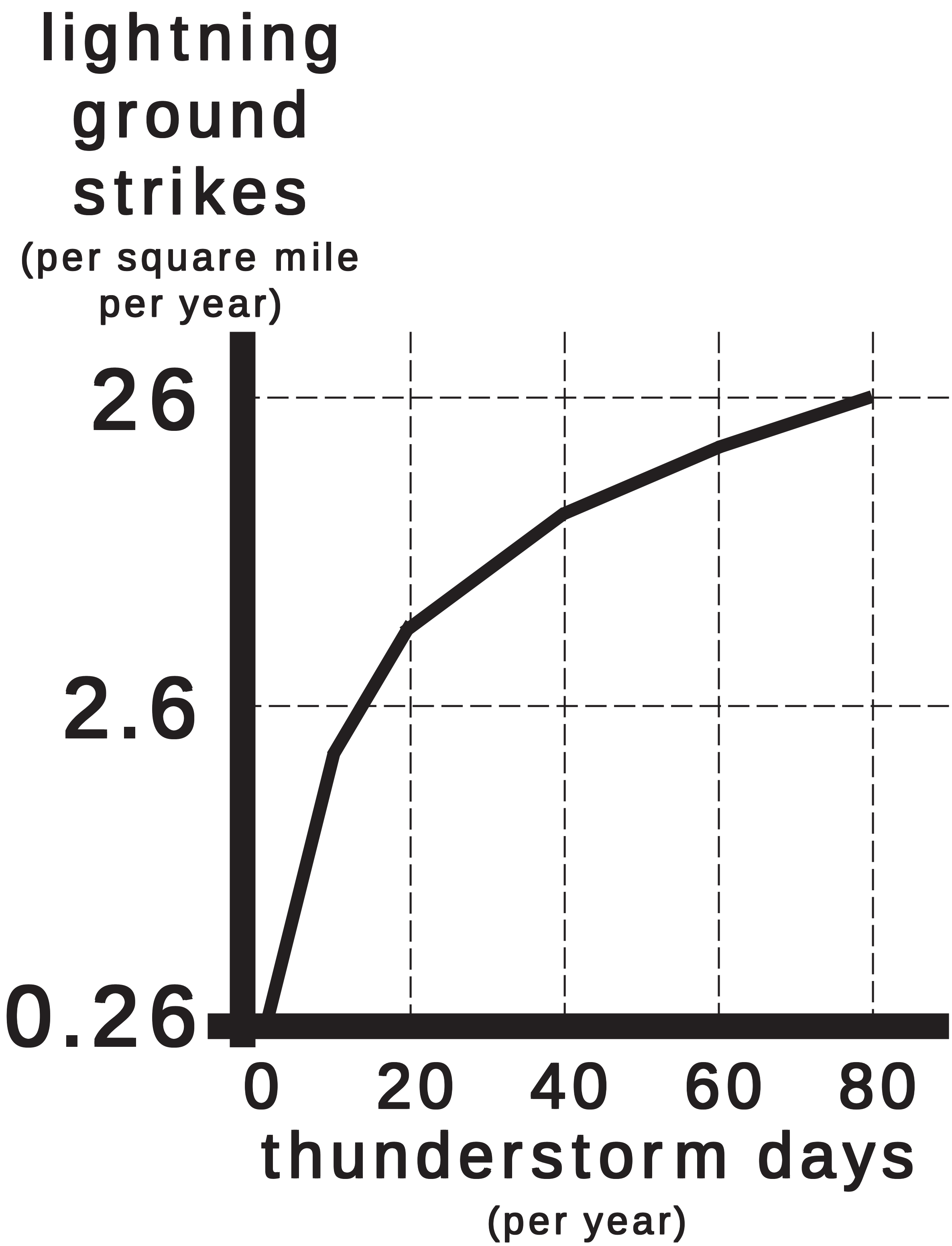


Figure 16: Annual lightning ground flashes compared with annual thunderstorm days. (Rakov & Uman 2013)

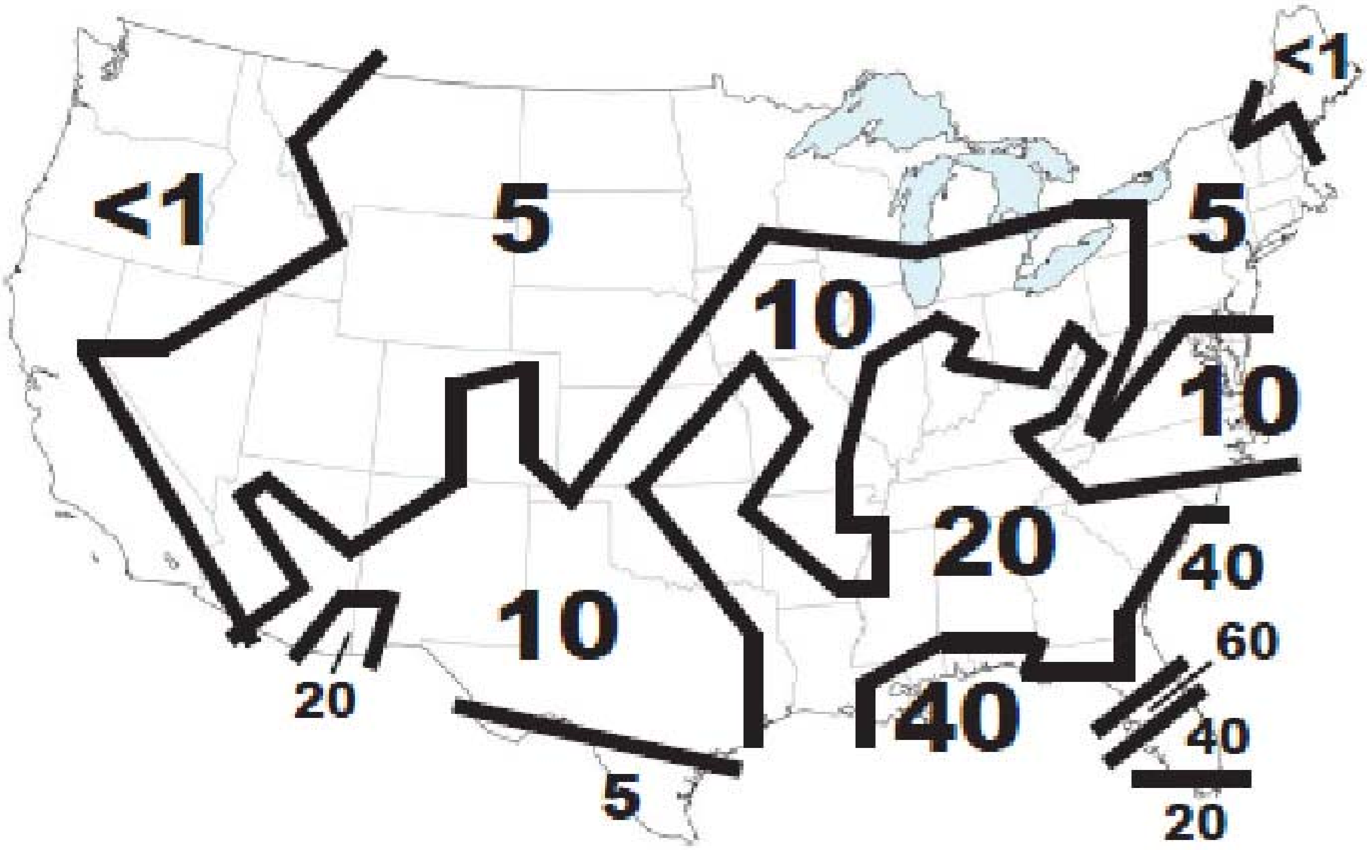


Figure 17: Cloud to ground lightning stikes per square mile per year. (1997-2007 national data)

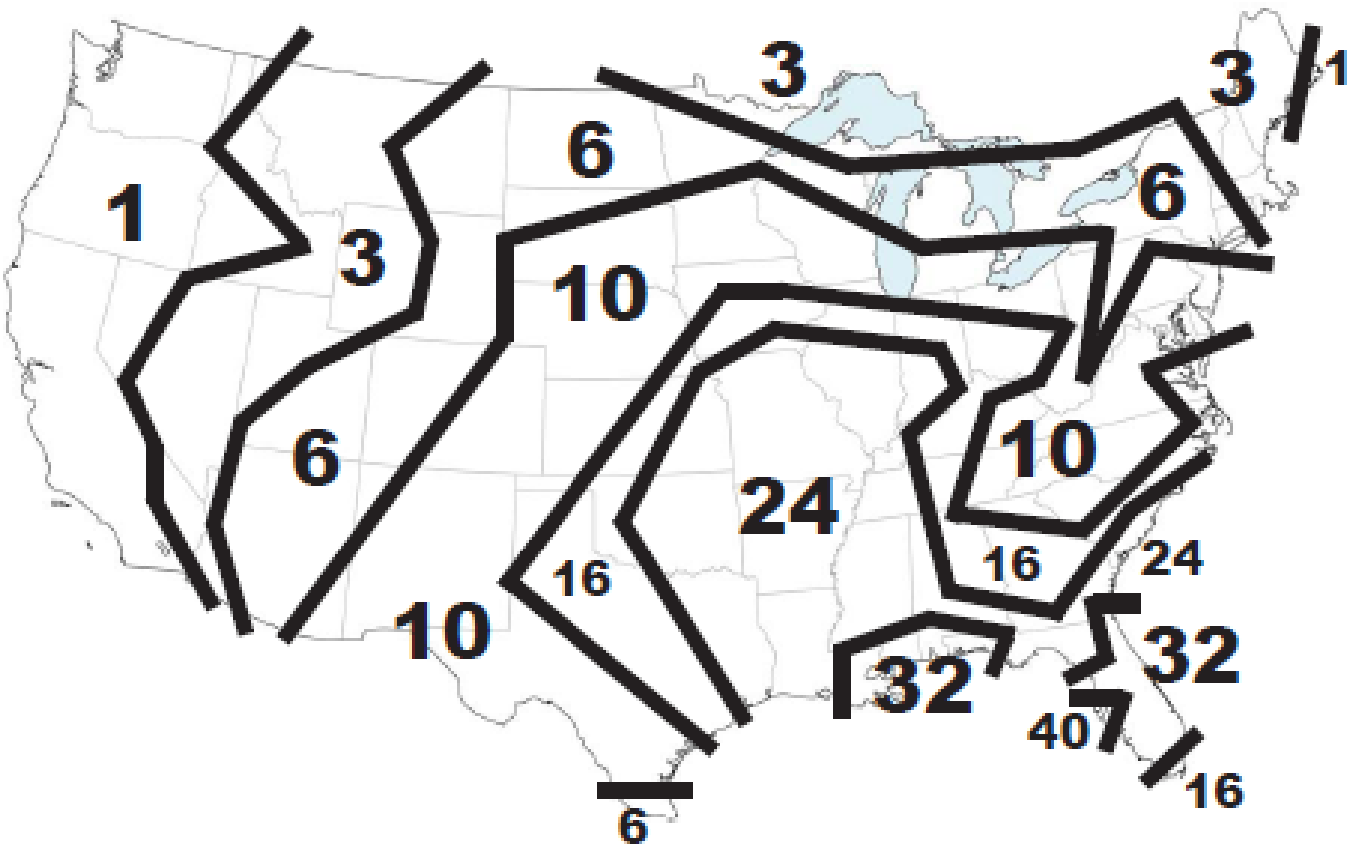


Figure 18: General cloud to ground lightning strikes
per square mile per year (national data of past 15 years)

Small, charged ice crystals are blown to the top of the cloud while larger, opposite charged particles fall toward the middle and base of the cloud. Figure 19 shows a simple way of considering how charges are separated within a storm cloud. A lightning ground strike occurs when electric charge fields in storms and at the ground surface connect across the atmosphere.

Separation of Charges

Charge separation in a cloud is accomplished by many different sized particles being slammed against each other in the updraft and turbulence of a storm cloud. Figure 20 shows representations (not to scale) of neutral cloud particles. Small water droplets, larger graupel (wet ice), and tiny ice crystals. Collisions between falling graupel (wet ice particles 1/12 to 1/6 inch in diameter) and rising small ice crystals (ice particles 1/400 of an inch in diameter or smaller) generate electrical charge separation. Peak negative charges are concentrated between cloud temperatures of 23^{o}F and -13^{o}F.

Lower in a cloud and at a greater than 5^{o}F temperature, ice crystals (and polarized water droplets) colliding with graupel remove a negative charge from the graupel. Figure 21. Higher in the cloud where temperatures fall below 5^{o}F, ice crystals banging into graupel leave a negative charge and carry a positive charge. These unbalanced charges are quickly blown apart by wind / updarfts. Ice crystals are carried toward cloud tops and graupel falls to mid and lower cloud zones. Within a cloud, positive and negative charge separations become more pronounced. Figure 22 shows positive and negative charges separated in a cloud by miles of air volume.

Tri-Pole

In its most simple form, charge separation within a storm cloud generates three poles: one mid-height negative charge zone; one high positive charge zone; and one much smaller positive charge zone near the cloud base. Figure 23. As the cloud moves over the landscape, its charge centers generate an opposite charged field beneath the cloud following along the ground. The ground charge size mirrors the size of the cloud charge centers. Figure 24.

An example of a positive electric field charge flowing along beneath a storm cloud with a well developed negative charge center is given in Figure 25. This positive charge wave follows and flows ups landscape objects like trees (i.e. enhances local electrical field). The distance away from storm cloud center electric field changes can be measured. Because a cloud has tripole charge centers, the total electric field moving on the ground below the cloud has a double positive peak and single negative peak. Figure 26. Negative lightning is common just before and just after storm center. Figure 27 summarizes cloud charge centers, altitudes of each center, and temperature zones of the charge centers.

Types of Lightning

Lightning occurs in a number of forms or varieties. There are internal cloud, cloud-ground, cloud-cloud, and cloud-air exchanges. Most lightning (60%) is inside one cloud's electrical system. Lightning which damages trees are cloud-ground exchanges. Cloud-ground exchanges begin 90% of the time as a cloud leader with a negative polarity charge. Most of the rest of cloud-ground lightning (9%) begins as a strong positive polarity cloud leader. About one percent of lightning exchanges are initiated from ground streamers. This rare form of ground-cloud lightning can have positive or negative polarity. (Uman 1971,1987). Trees less than 325 feet tall are almost always struck by negative polarity cloud leaders. (Uman 2008). This manual deals almost exclusively with this most common negative polarity cloud-ground exchanges.

As mentioned above, positive lightning comprises an average of about 9% of all strikes. The positive strike distribution over the year is highly variable. Figure 28 shows positive lighting strike averages over the United States per year. Positive lightning strikes are relatively high (23% of all strikes) in Winter months and low (7%) in Summer months July and August.

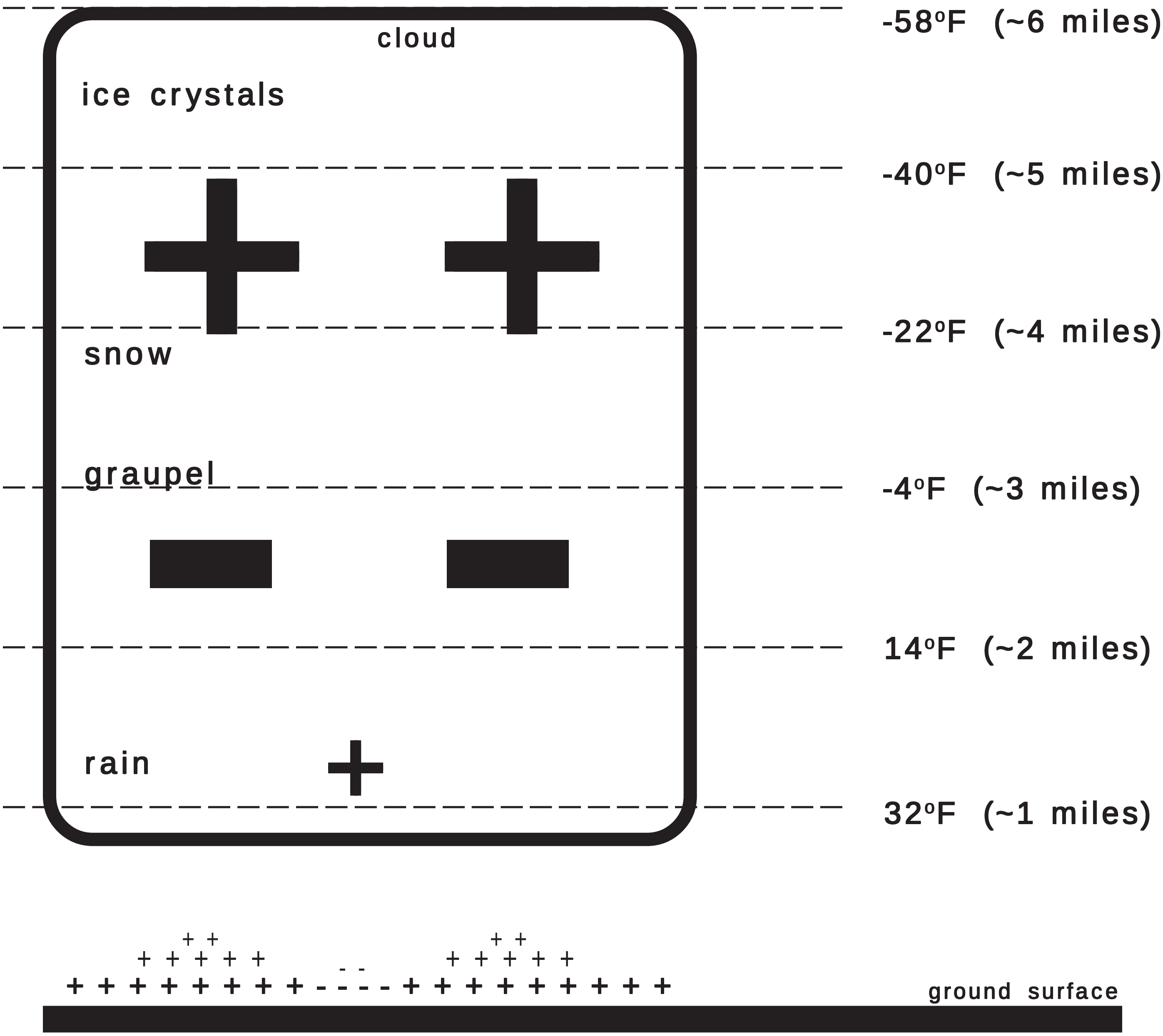


Figure 19: Charge separation inside a cloud leading to lightning strikes. Altitude in miles, temperature, and precipitation form are given.

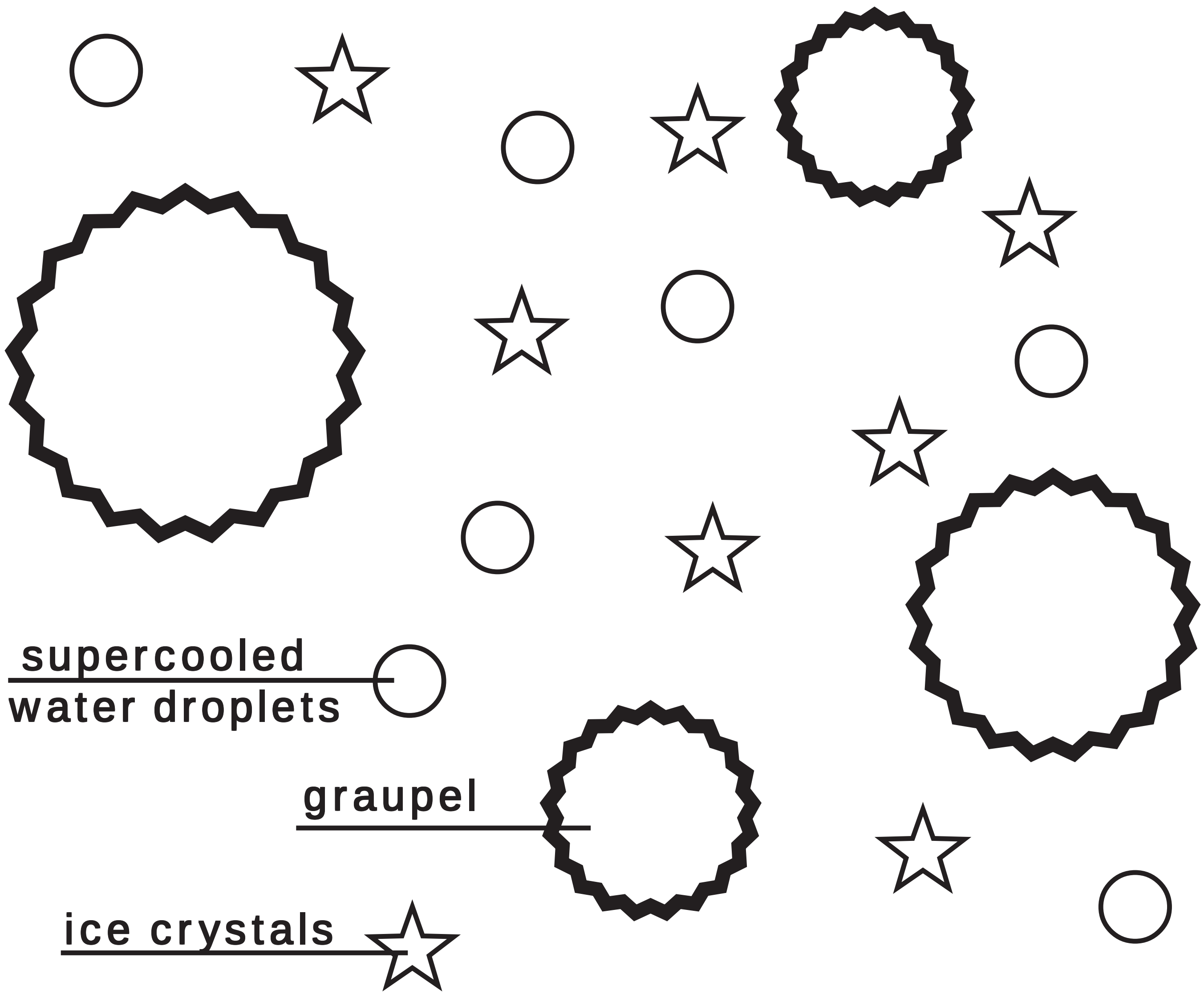


Figure 20: Particles in a cloud include supercooled water droplets,graupel (wet ice), and ice crystals all initially with a neutral charge. (Mansell & MacGorman 2012)

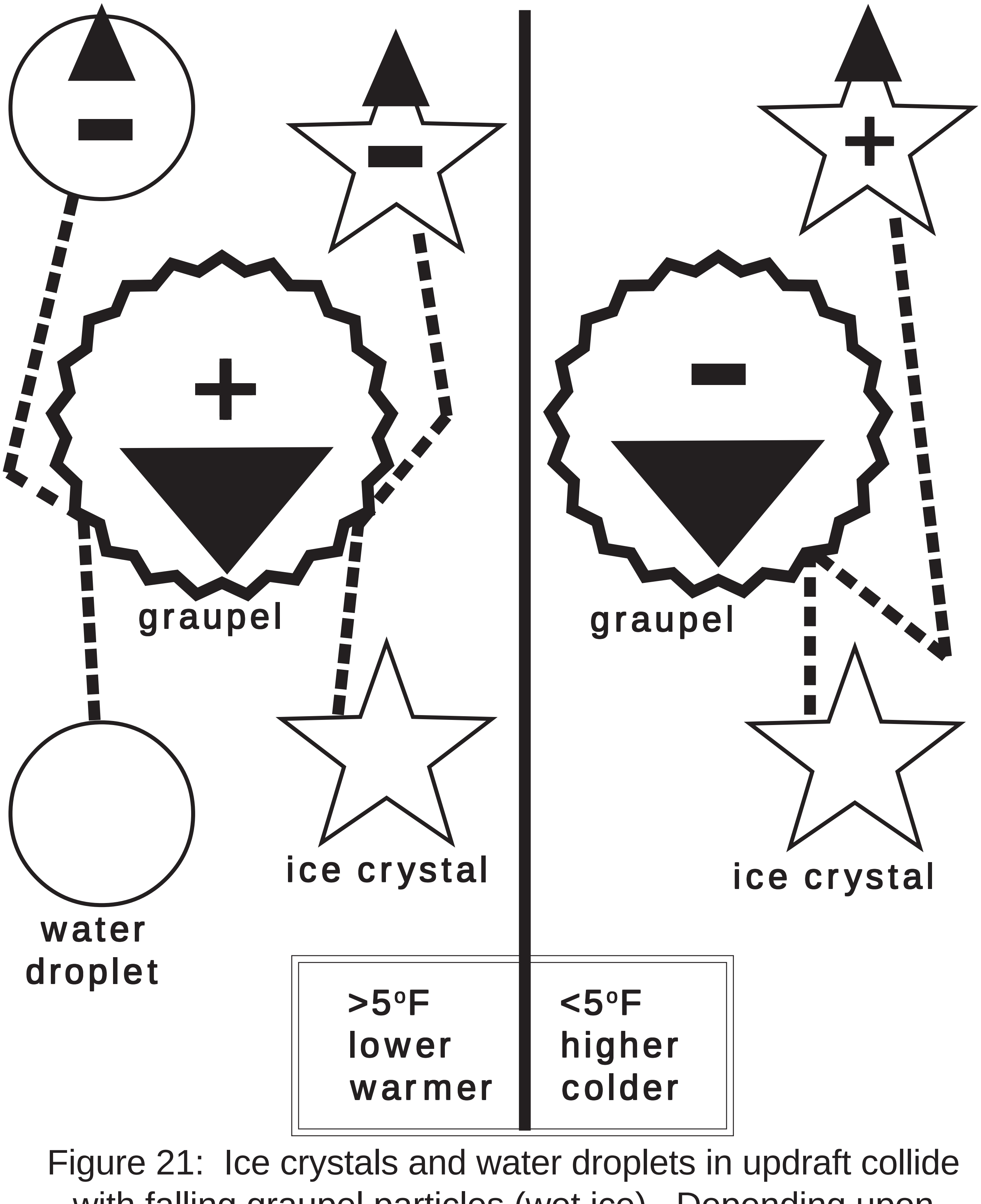


Figure 21: Ice crystals and water droplets in updraft collide with falling graupel particles (wet ice). Depending upon temperature (greater or less than 5°F), graupel, water droplets, and ice crystals collect different charges.
(Mansell & MacGorman 2012; Rakov & Uman 2003)

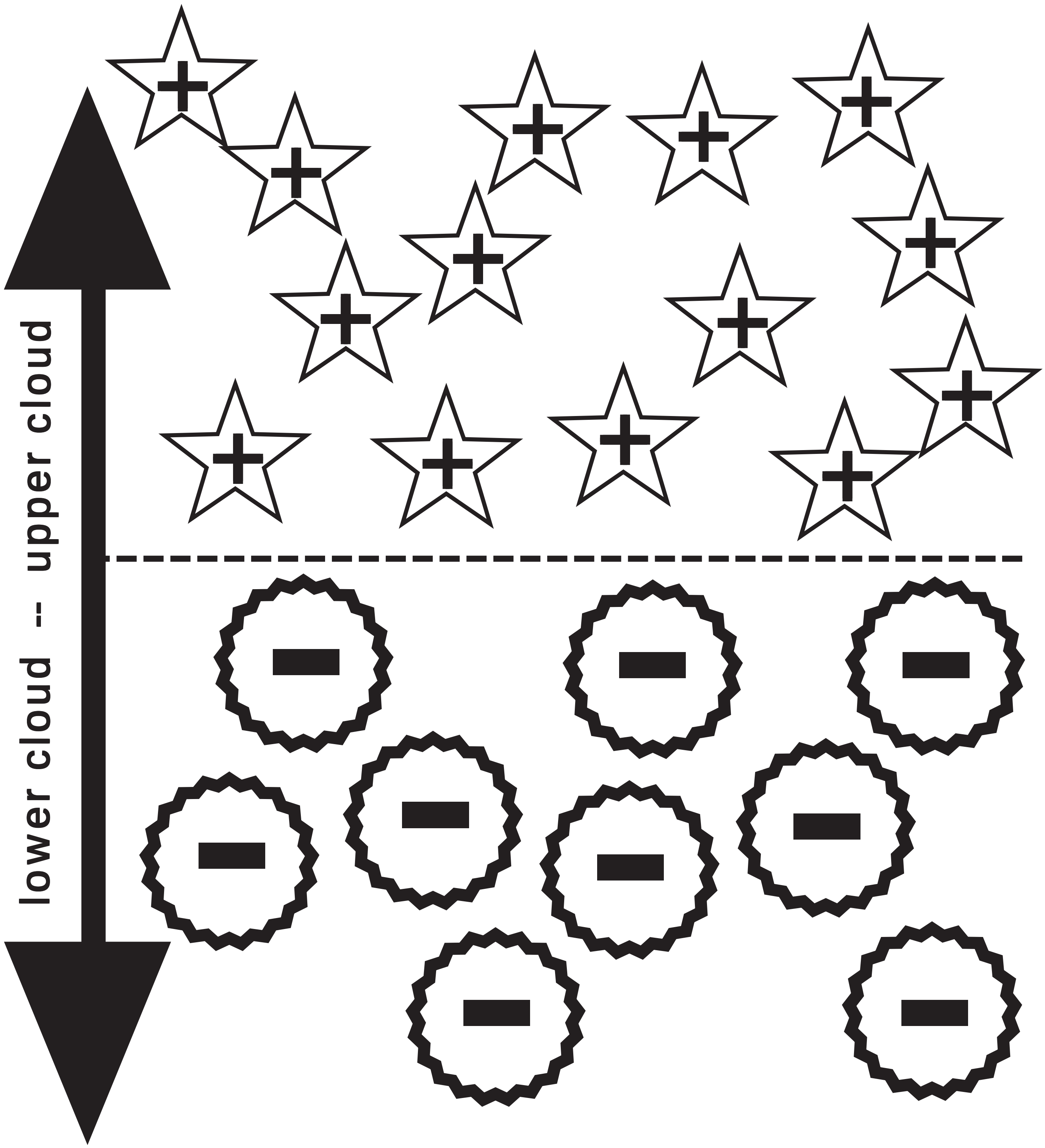


Figure 22: Charged particles become separated and concentrated inside cloud. (Mansell & MacGorman 2012)

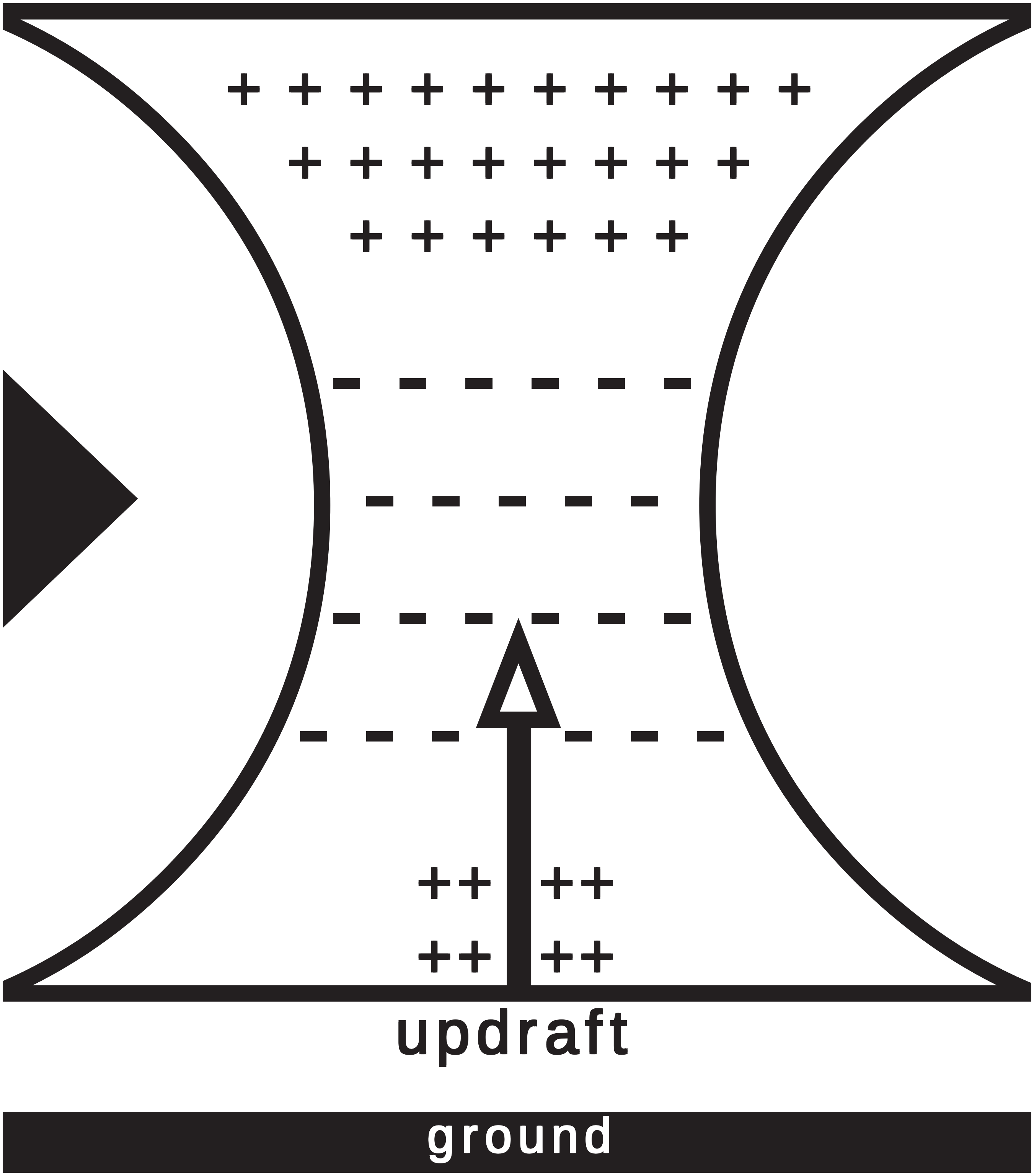


Figure 23: Simplified charge structure of thunderstorm.
(Rakov & Uman 2003)

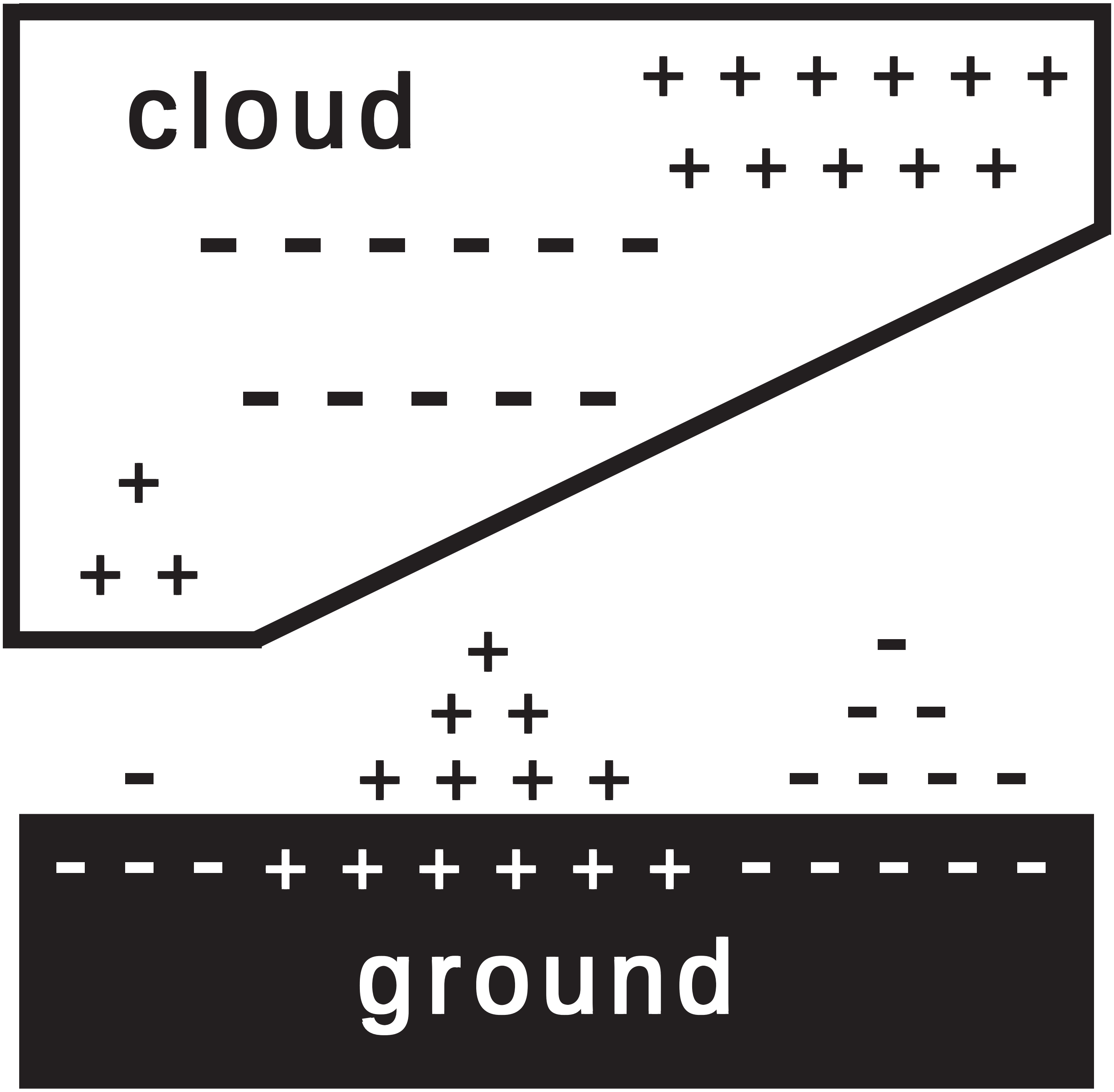


Figure 24: Electric field change along ground in response to cloud charges. (Rakov & Uman 2003)

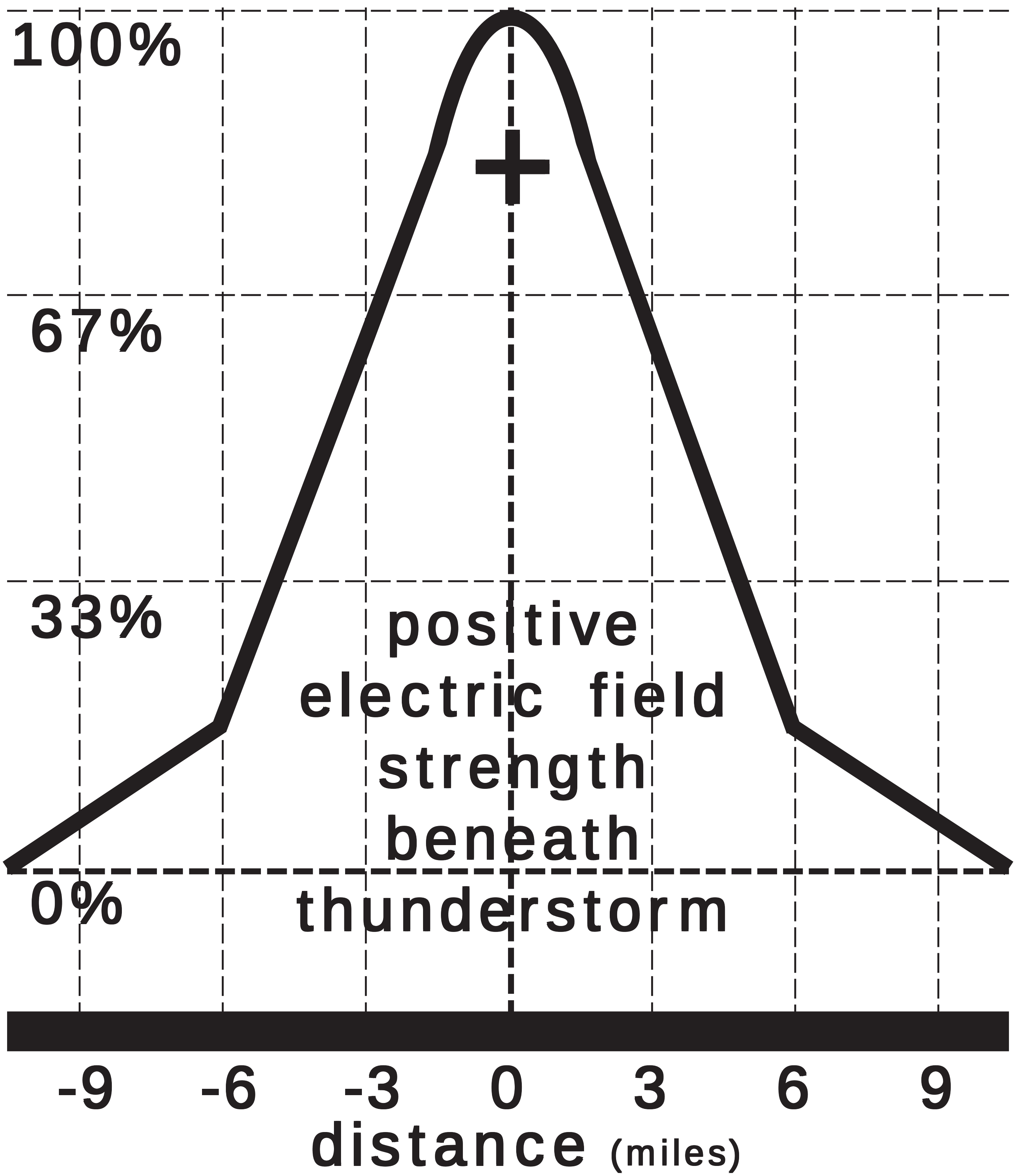


Figure 25: Relative electric field change along ground beneath thunderstorm's negative center as it moves.
(Rakov & Uman 2003)

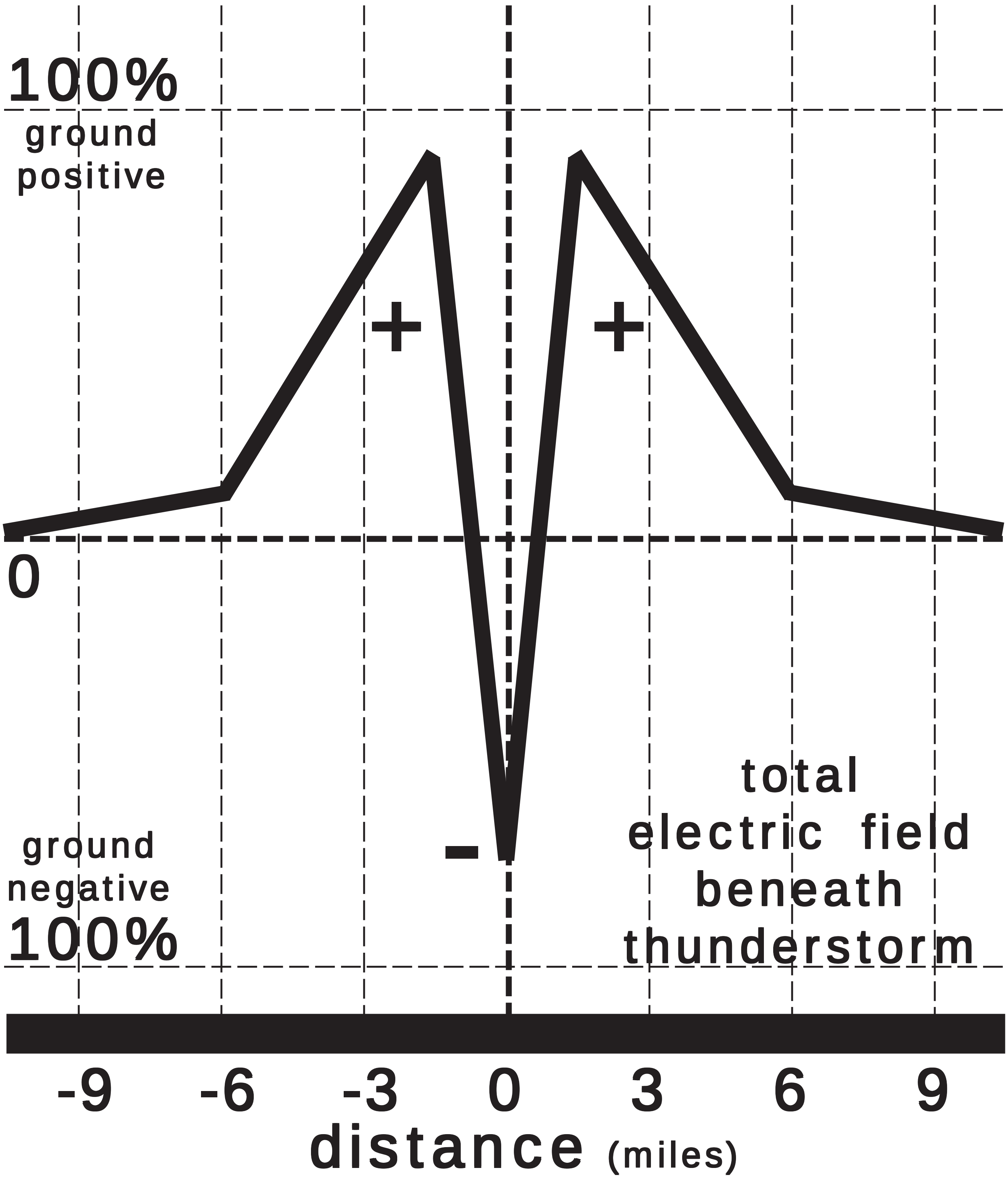


Figure 26: Relative electric field change along ground beneath thunderstorm's primary negative and primary and secondary positive centers as it moves.
(Rakov & Uman 2003)

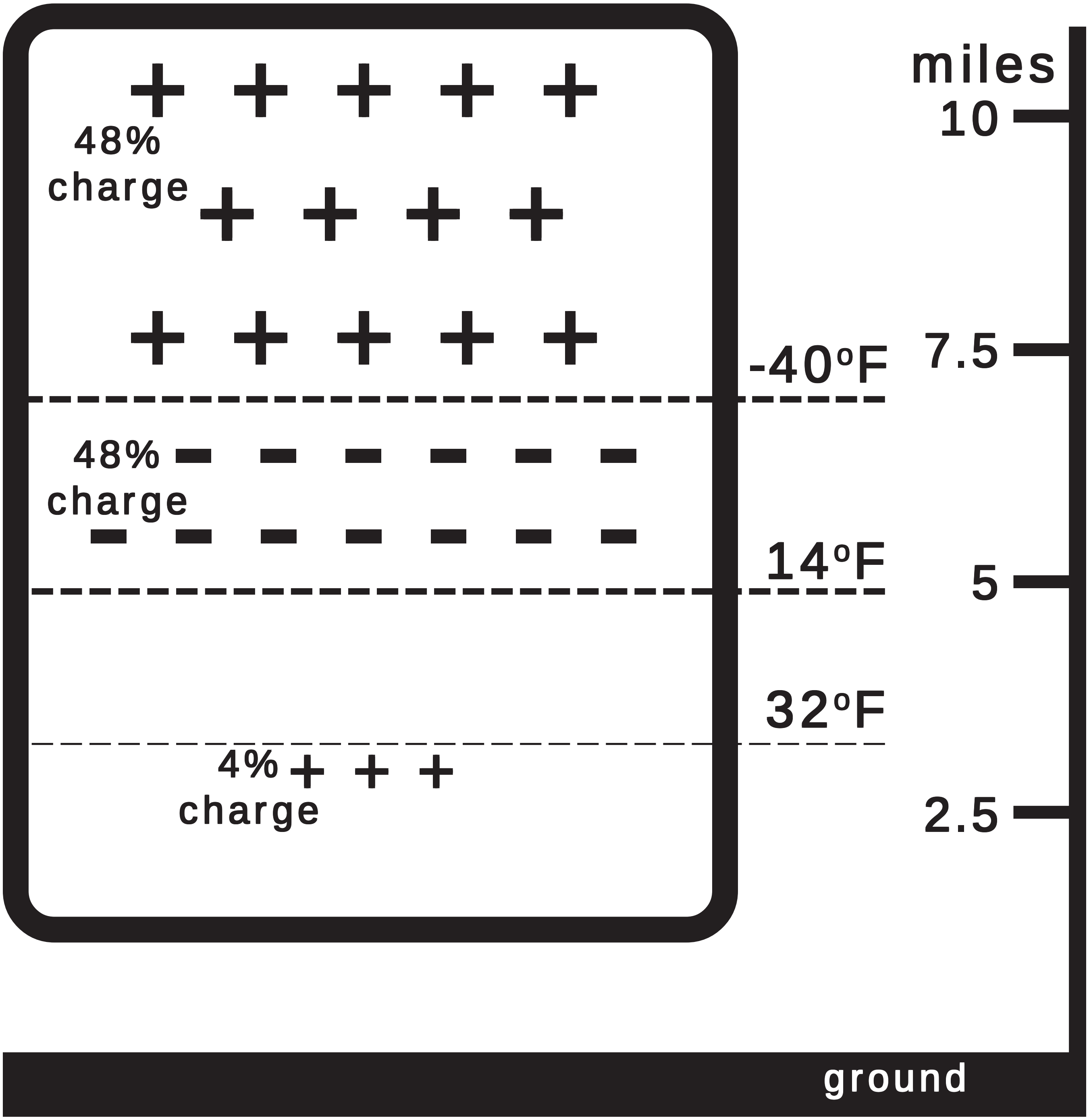


Figure 27: Basic thunderstorm charge structure by altitude and temperature. (Rakov & Uman 2003)

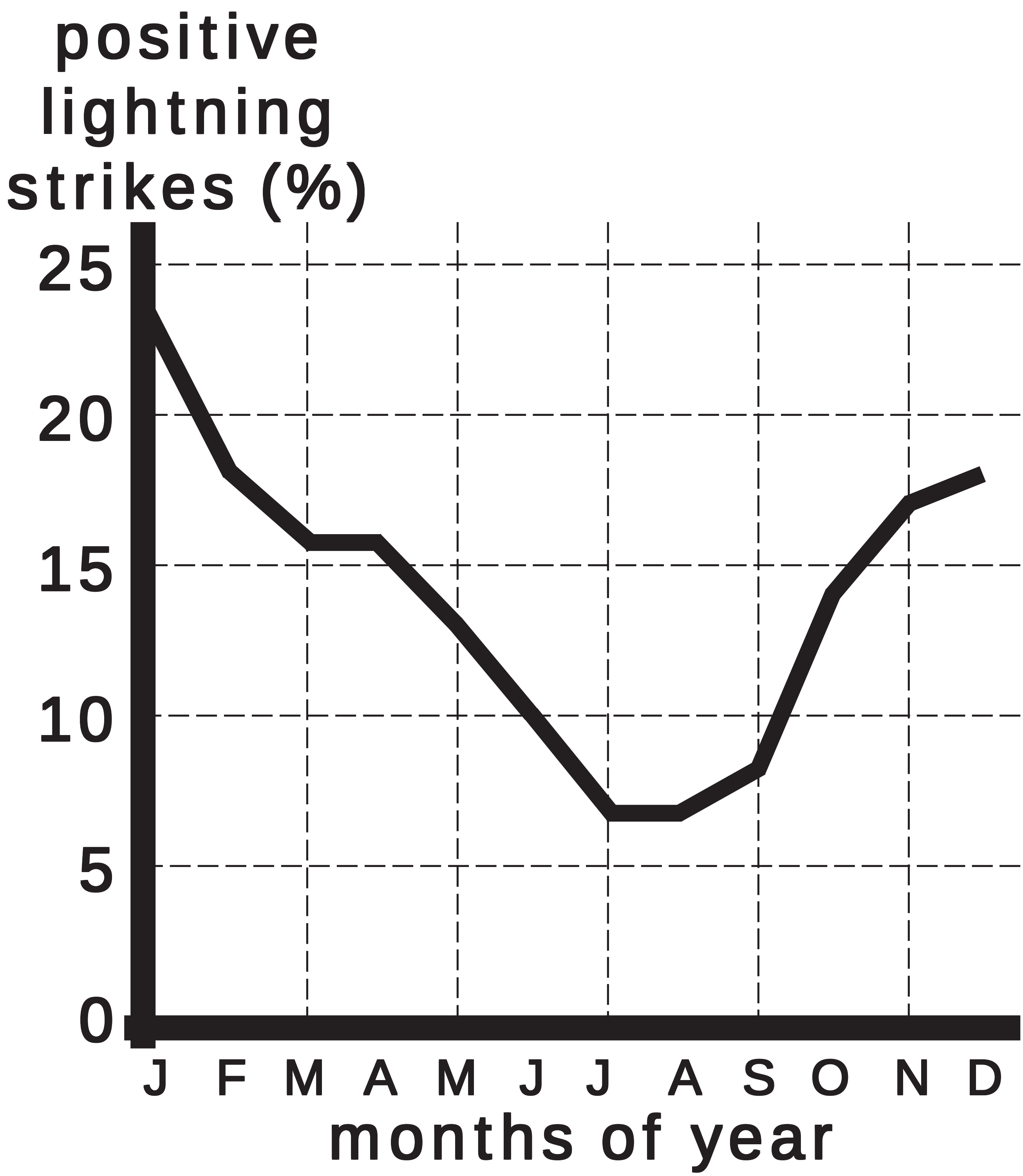


Figure 28: Average percent of positive lightning flashes over the United States annually. (derived from Rakov & Uman 2003)

Example Real Storm Data

The distribution of negative and positive lightning strikes in a storm varies by storm types and charge center positions in clouds. Figure 29 provides an example of a storm system which spawned lightning, hail, and a F5 tornado in the Midwest over a 4.5 hour period. Positive lightning occurred early in the storm and peaked just before storm midpoint and just short of major hail and tornado events. The negative lightning peak was much greater in number of strokes than positive lightning and peaked well after the middle of the storm toward the end.

Strike Strength

Figure 30 provides a comparison of lightning current values of both positive and negative polarity strikes. Note the positive lightning can reach extremely large current values compared with negative lightning. The average of positive and negative are relatively close to the same (~30,000amps (30kA) negative and ~35,000amps (35kA) positive), but the range expected is much greater in positive lightning.

For negative lightning, there is a significant difference between the first stroke and subsequent strokes within the same strike. Figure 31 provides the probability and currents of first and secondary strokes. With average current loads, the difference between first and secondaries can be greater than 10kA. The first stroke carries the largest current. The international lightning protection standards use a different shaped curve for negative first stroke lighting. Figure 32. This figure places the probability tails on the curve.

Probabilities

Another means of appreciating different peak currents in lightning is by examining the probability of a larger or smaller strike / stroke. Figure 33 provides the probability of exceeding a given current. For example from the figure, there is a 95% probability of exceeding 14kA for a negative first stroke. In other words, only 1 in 20 negative strikes will be less than 14kA. The 50% probability line provides a functional average of negative first stroke (30kA, secondary negative stroke (12kA), and positive single stroke / strike (35kA).

Note positive lightning can exceed 200kA 5% of the time. Also note the 50% probability values for the time needed to complete each stroke. It is clear from all values, positive lightning is much different from negative lightning and has potential for greater damage to trees.

Formation Events

The formation of a negative cloud to ground lightning strike contains two strokes begins with a strong distribution and separation of charges, both in the cloud and on the ground. Figure 34. Next, a negative cloud leader forms and begins to push toward the positive charges near the ground. Figure 35. The negative cloud leader continues to cross the distance between cloud and ground, following a zig-zag path of lowest resistance. Side charge channels also are formed and push downward. Figure 36. The positive electric field near the ground begins to form short streamers upward toward the negatively charged cloud leader, side leader, and cloud negative electric filed. Figure 37.

The two charge fields meet and attach, making a single charge exchange channel. Figure 38. The massive current exchange causes a light flash (arc) and neutralization of some of the cloud and ground charges. Figure 39. After a short pause, a second stroke of current exchange follows the same (or nearly the same) pathway, causing a second light flash and further neutralizing cloud and ground charges. Figure 40. The timing between the first and second stroke (negative polarity lightning) beginning in the cloud negative charge center is given in Figure 41. The times listed across the figure top are times in milliseconds.

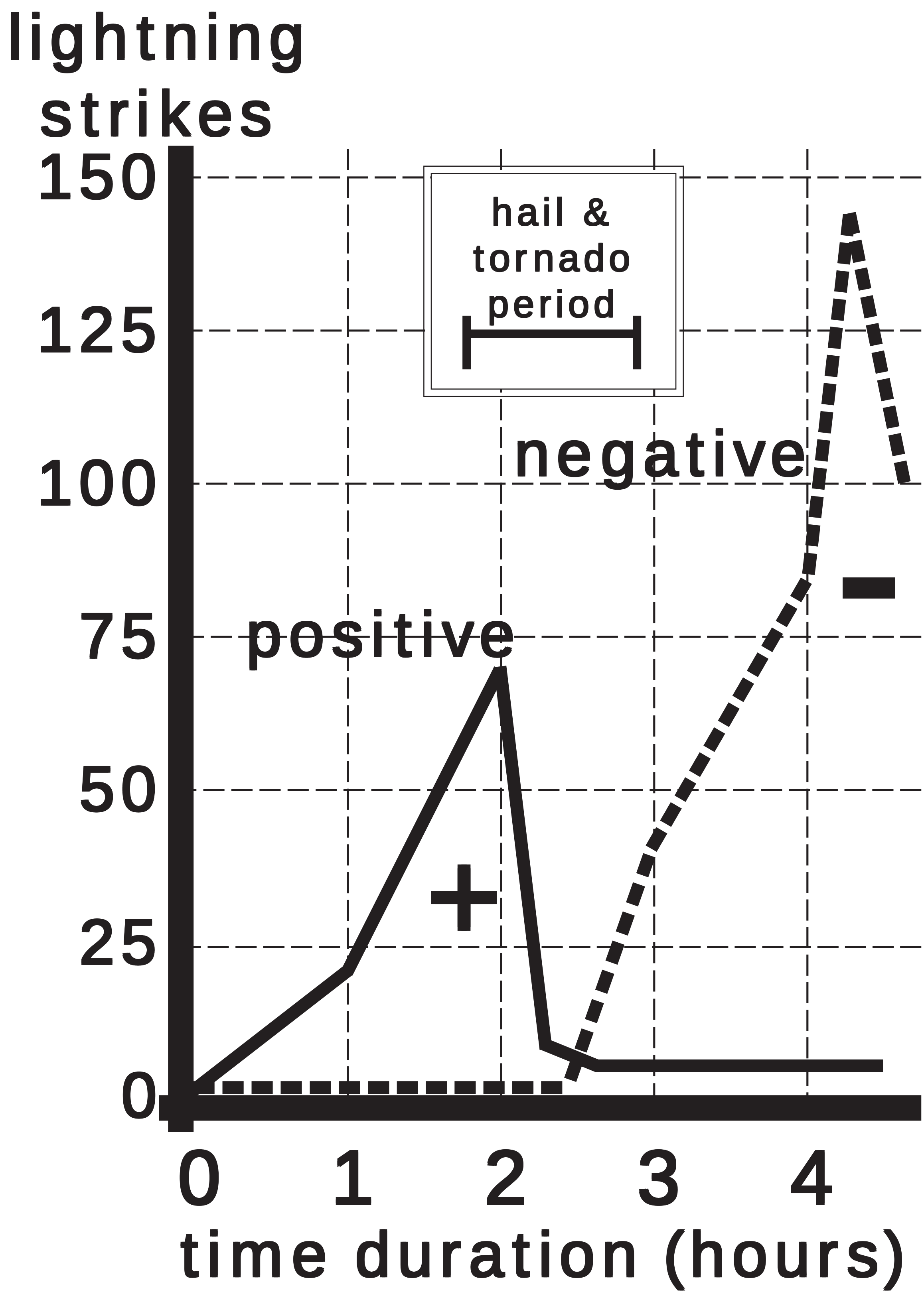


Figure 29: Number of positive and negative cloud to ground lightning strikes in one tornado generating storm.
(derived from Rakov & Uman 2003)

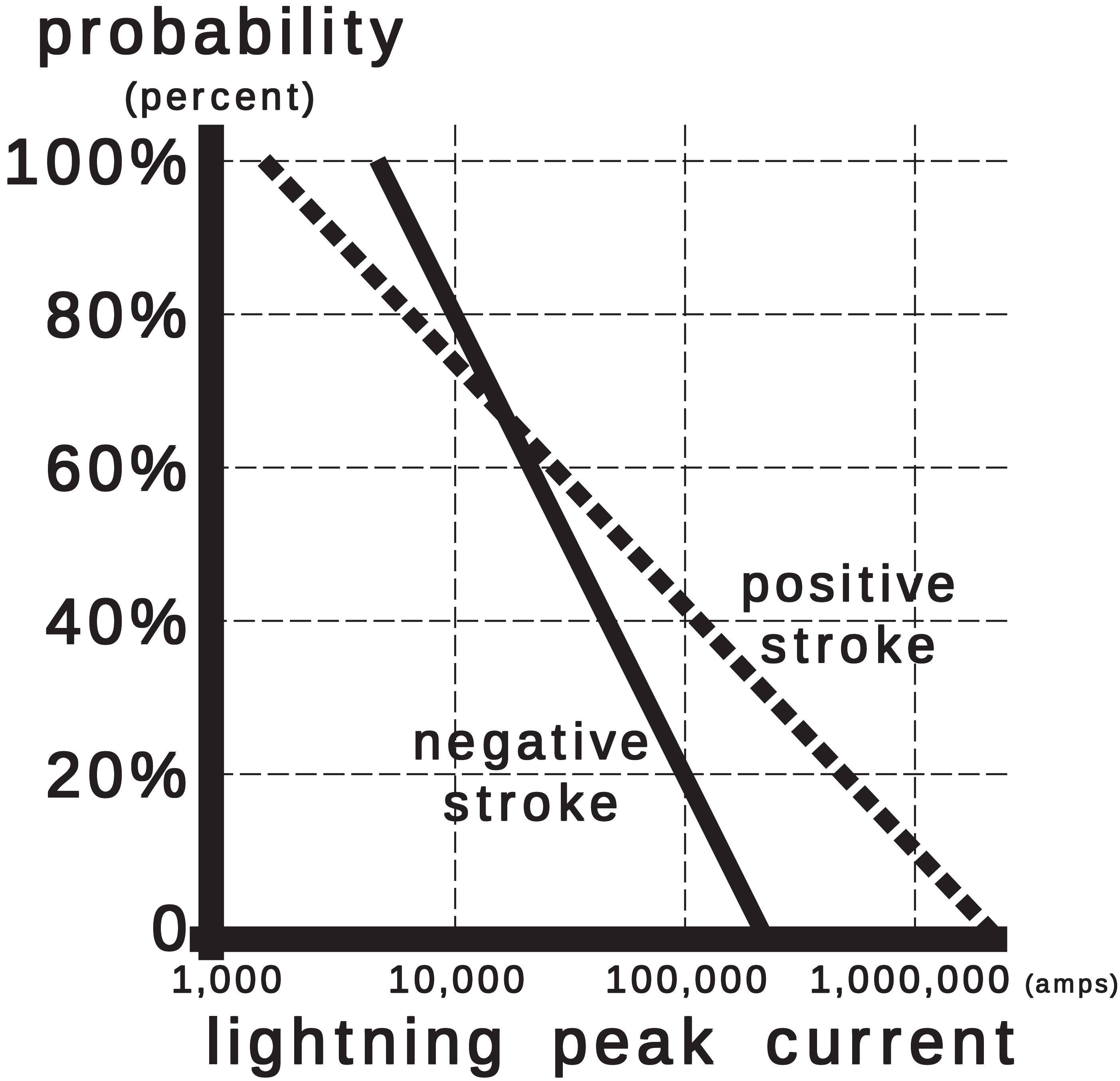


Figure 30: Lightning first stroke peak current percentages.
50% = ~30,000amps negative & ~35,000amps positive
(Rakov 2012)

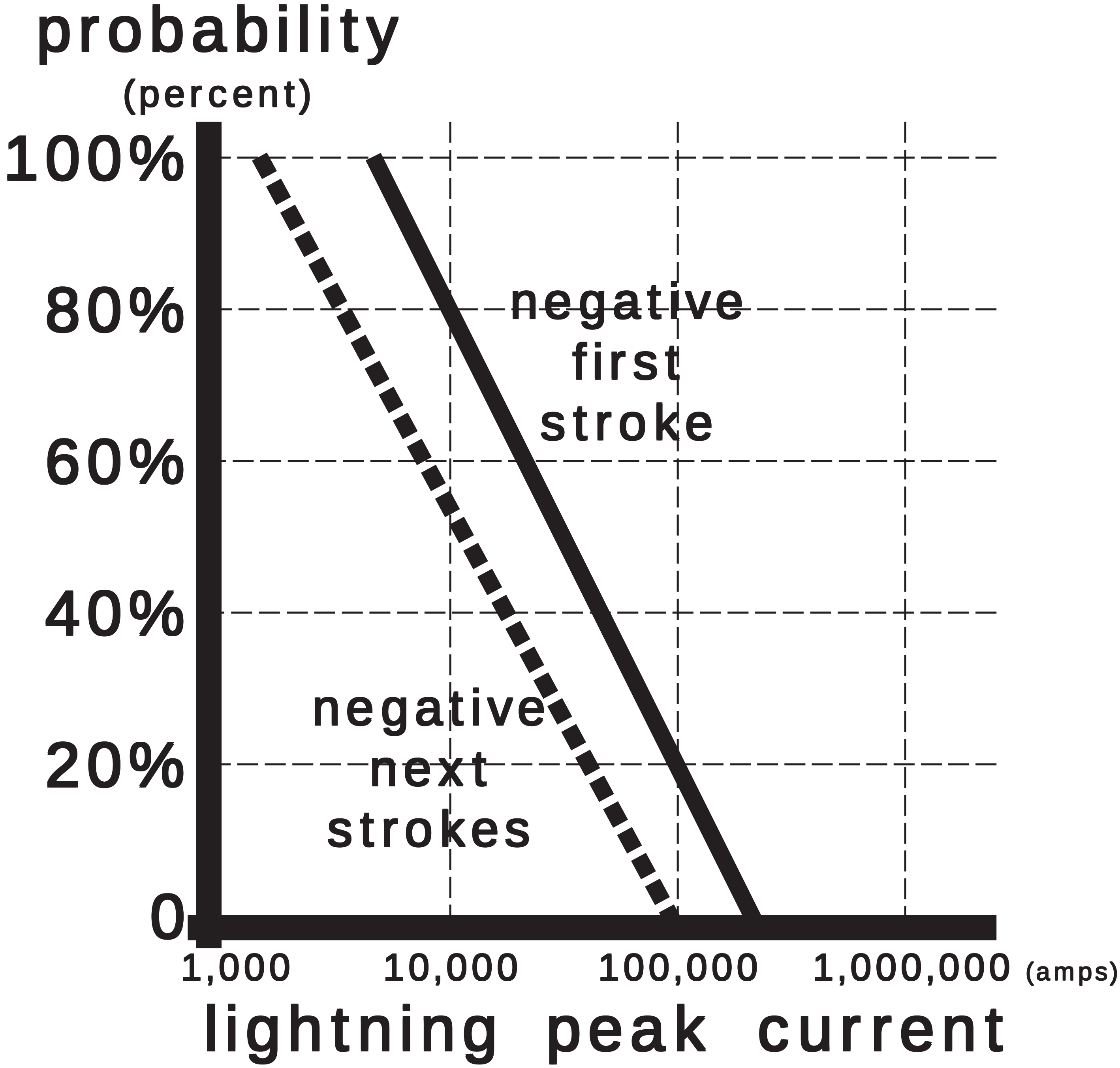


Figure 31: Lightning negative first and subsequent strokes peak current percentages. 50% = ~30,000amps first stroke & ~10,000amps second strokes (Rakov 2012)

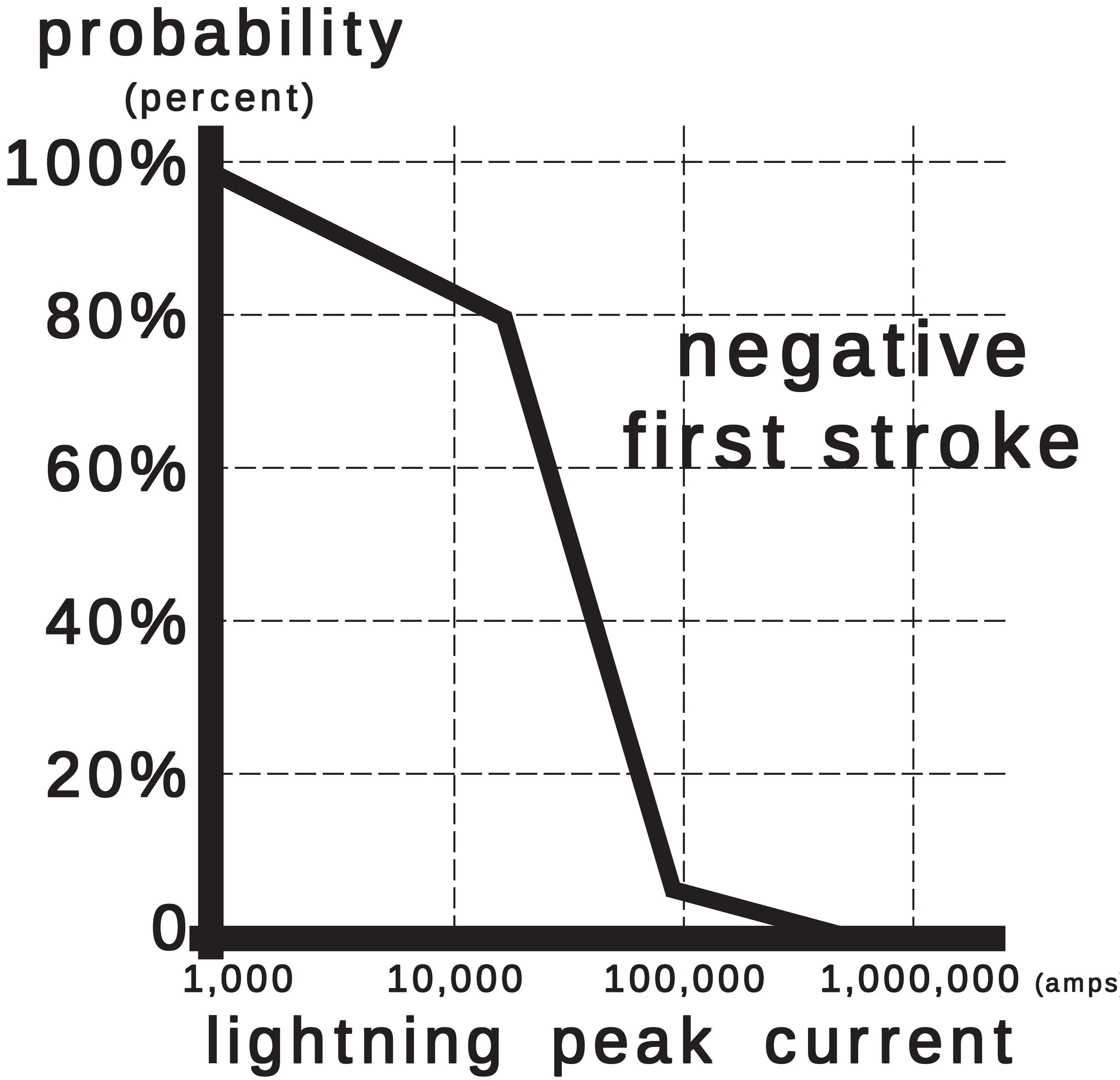


Figure 32: Negative lightning first stroke peak current percentages used in international lightning protection standards. 50% = ~31,000kA.
(Rakov 2012)

	percent exceeding value		
	95%	50%	5%
Peak Current (kA)			
negative first	14	30	80
negative seconds	5	12	30
positive first	5	35	250
Stroke duration (microseconds)			
negative first	30	75	200
negative seconds	7	32	140
positive first	25	230	2,000
Flash duration (milliseconds)			
negative first	0.2	13	1,100
negative seconds	21	180	900
positive first	14	85	500

Figure 33: Expected range of lightning values. The 50% probability value would represent the average.
(Rachidi & Rubinstein 2012; Rakov 2012)

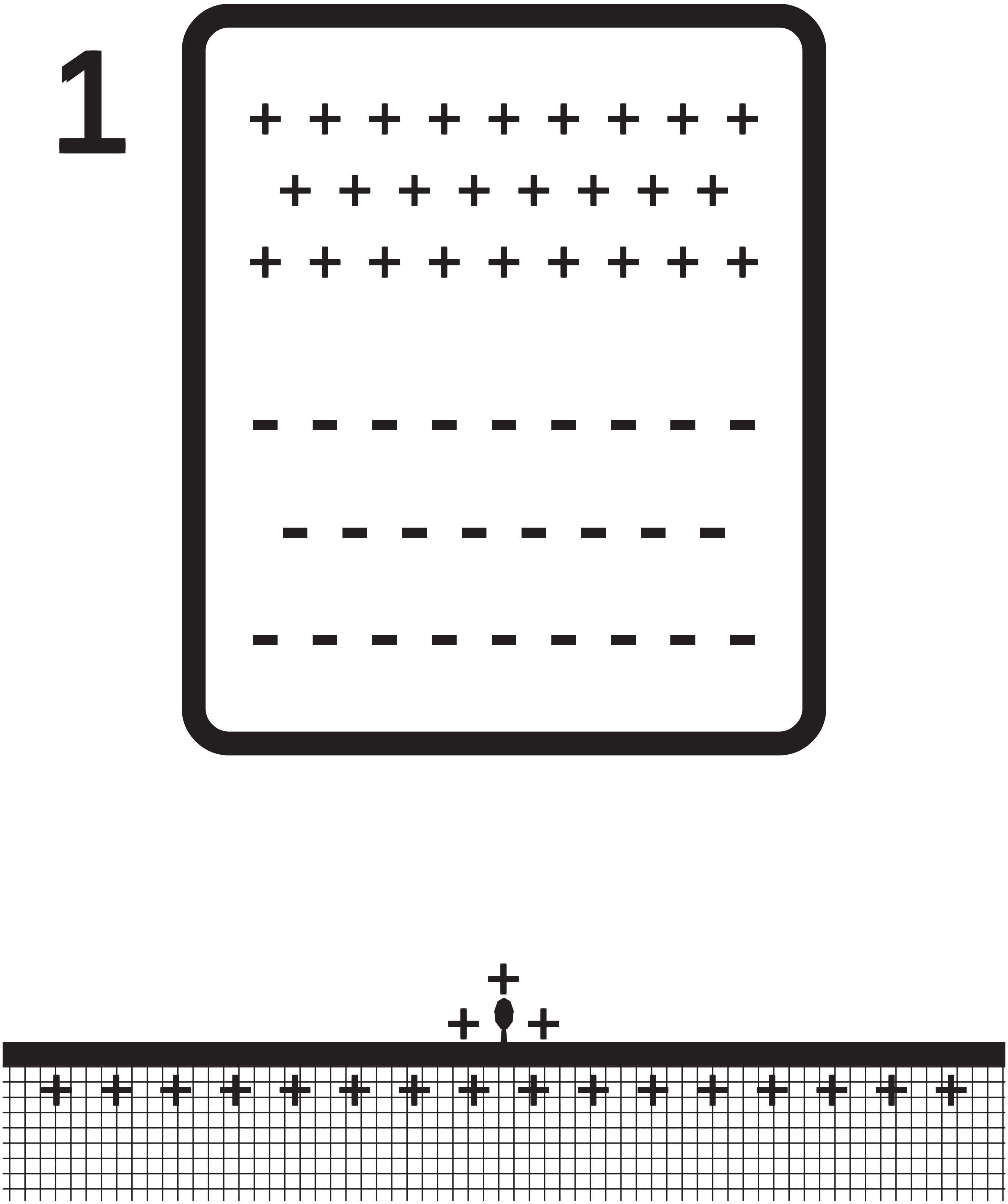


Figure 34: Formation of a negative cloud to ground lightning strike. (Rakov & Uman 2003)

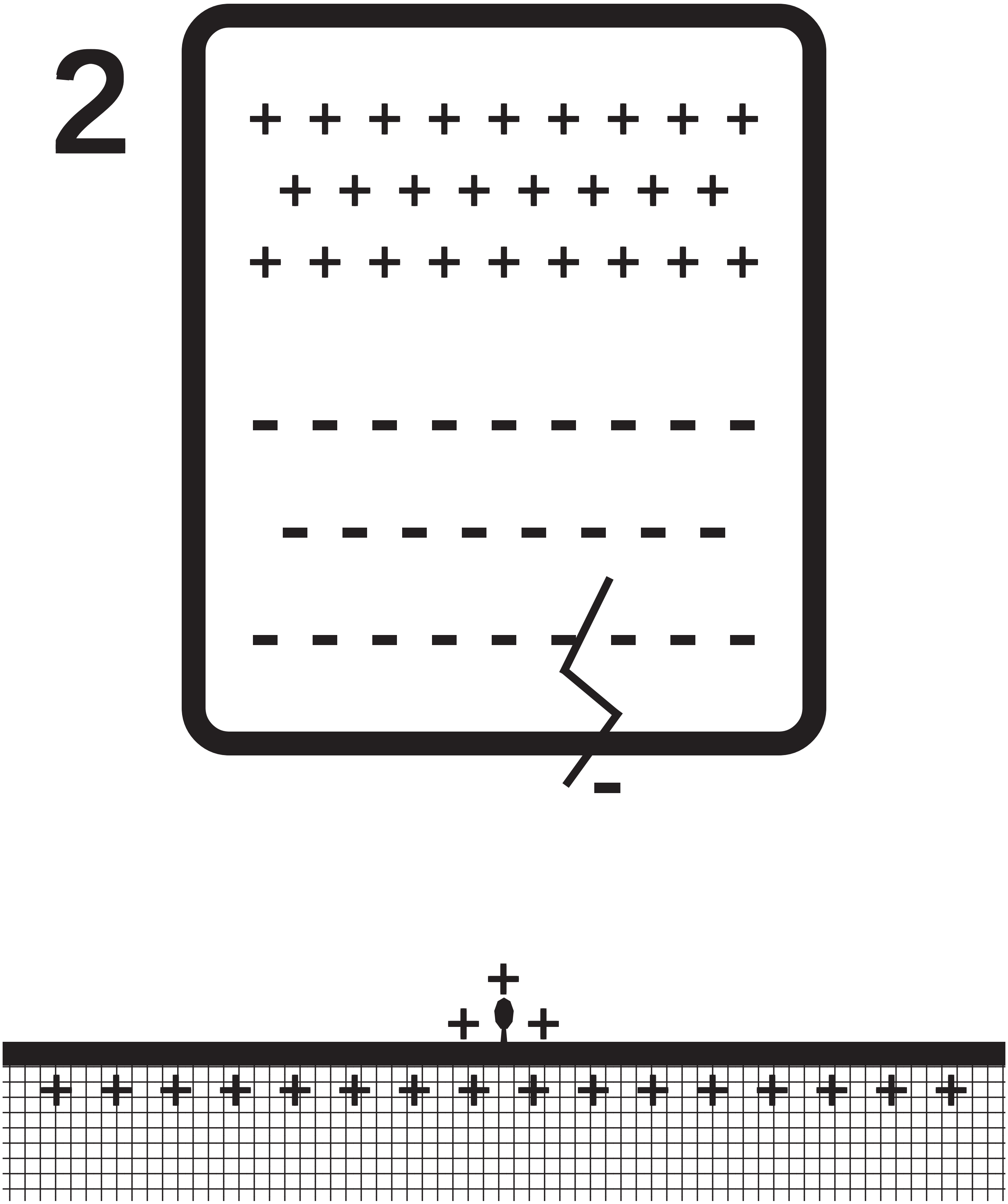


Figure 35: Formation of a negative cloud to ground lightning strike -- negative cloud leader. (Rakov & Uman 2003)

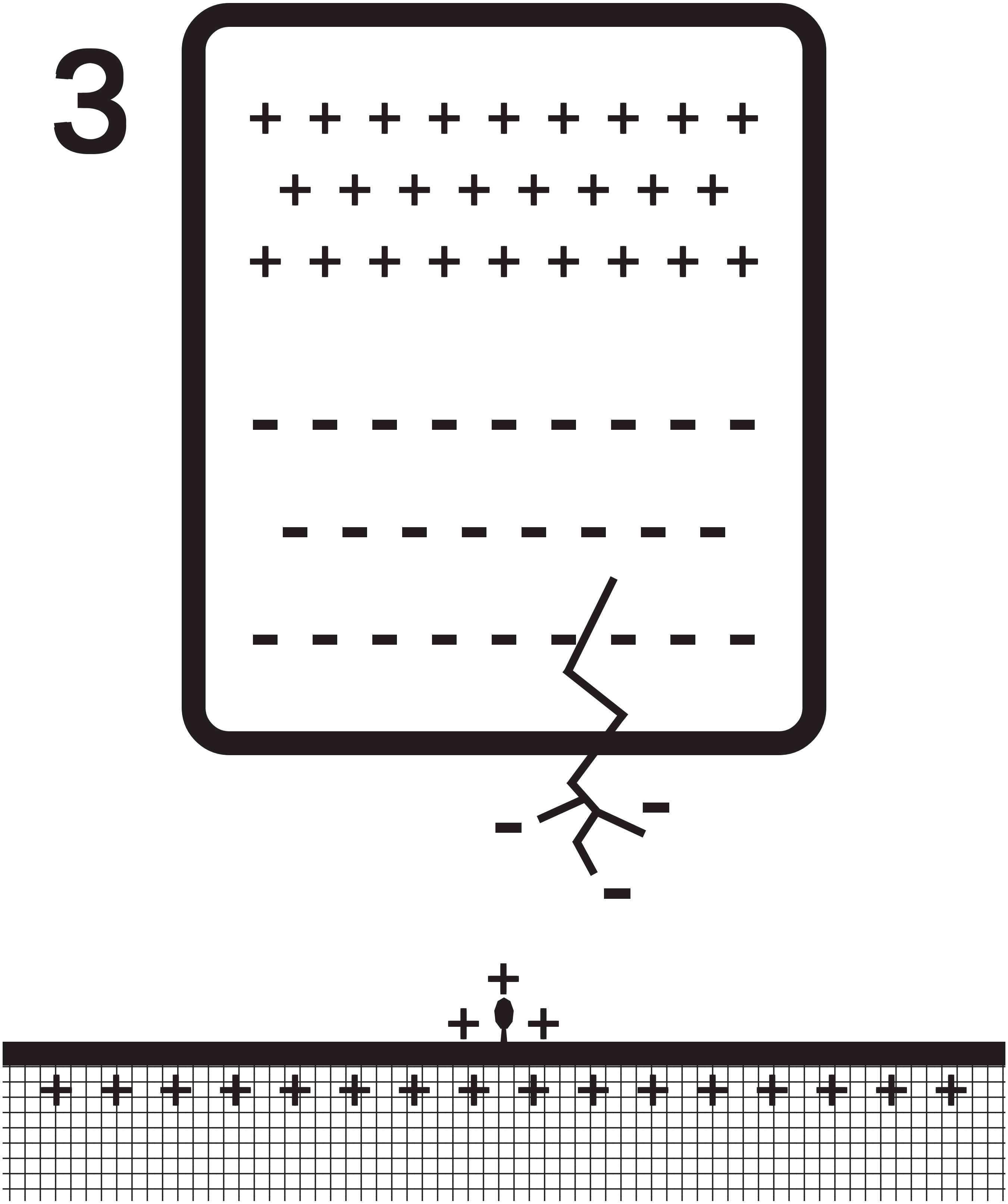


Figure 36: Formation of a negative cloud to ground lightning strike -- cloud leader stepped propagation. (Rakov & Uman 2003)

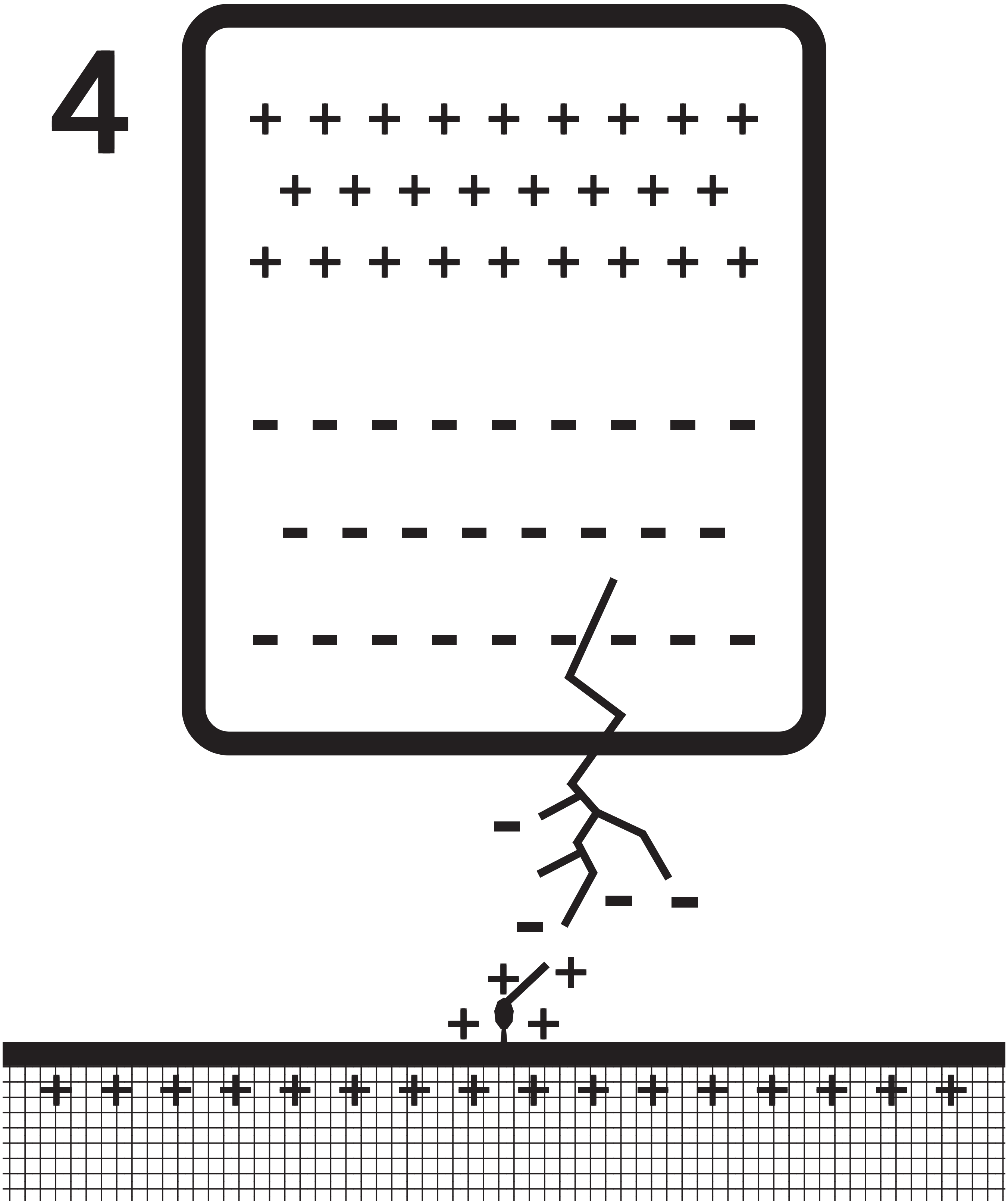


Figure 37: Formation of a negative cloud to ground lightning strike -- approach with ground streamer. (Rakov & Uman 2003)

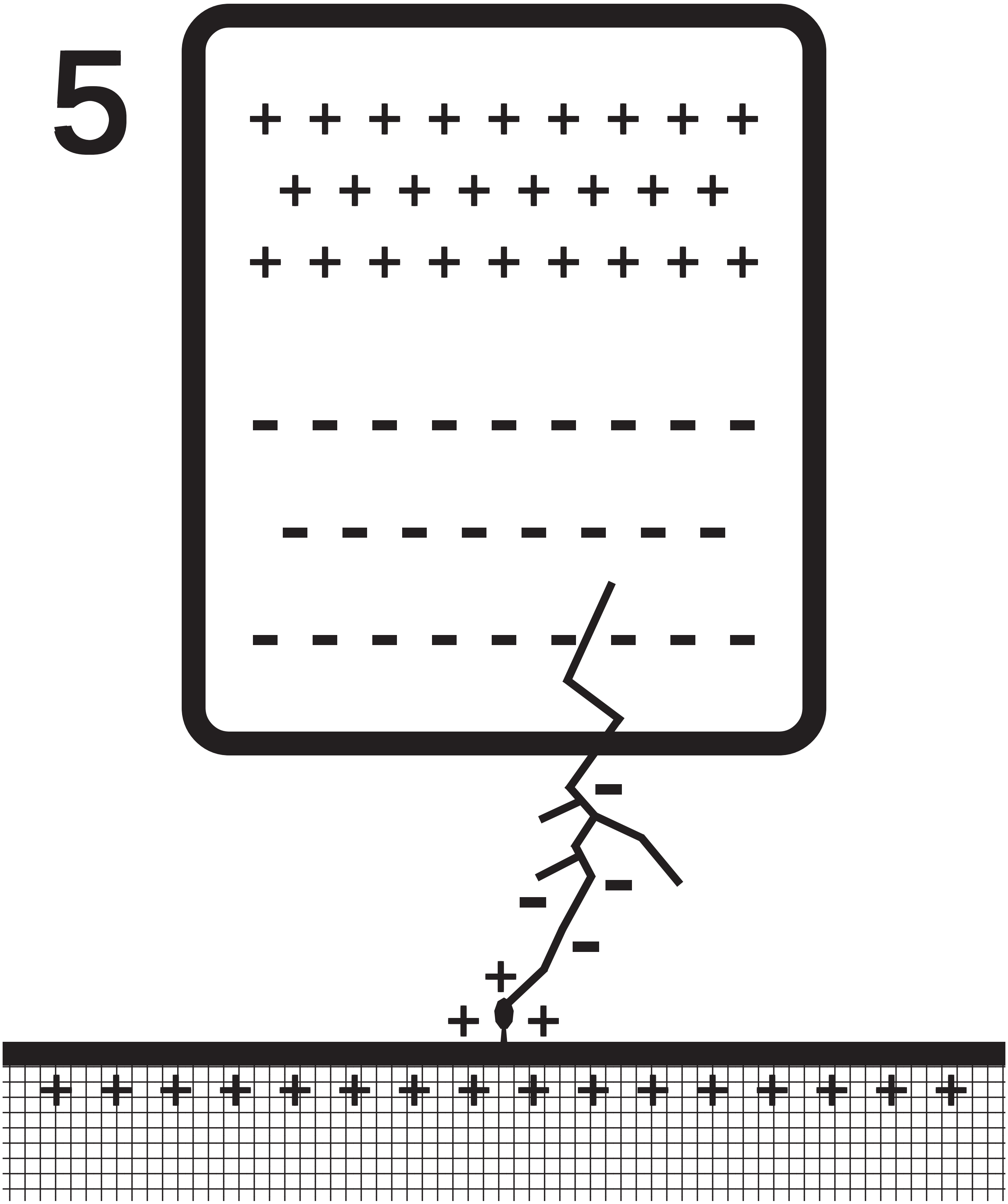


Figure 38: Formation of a negative cloud to ground lightning strike -- attachment. (Rakov & Uman 2003)

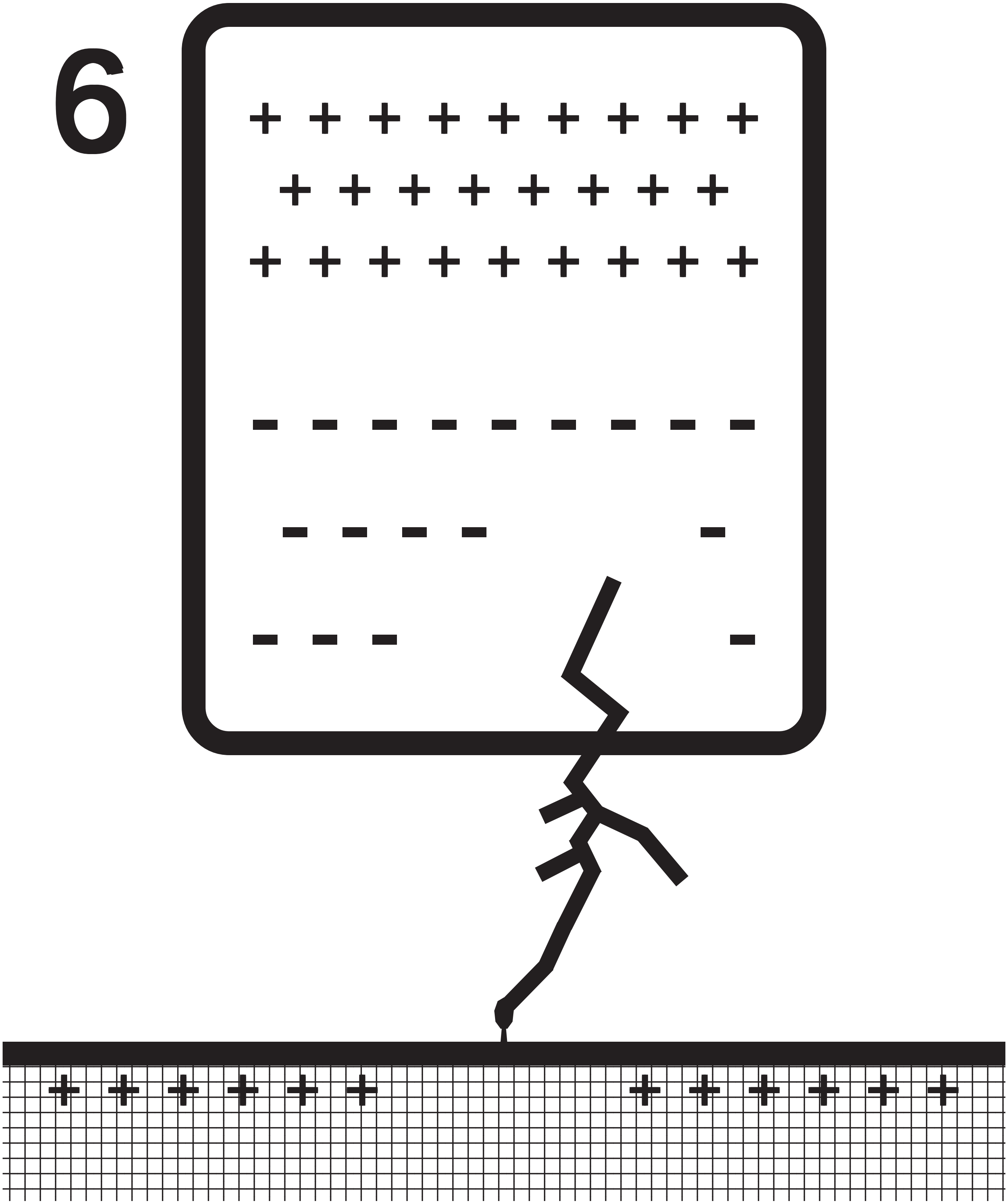


Figure 39: Formation of a negative cloud to ground lightning strike -- first stroke exchange. (Rakov & Uman 2003)

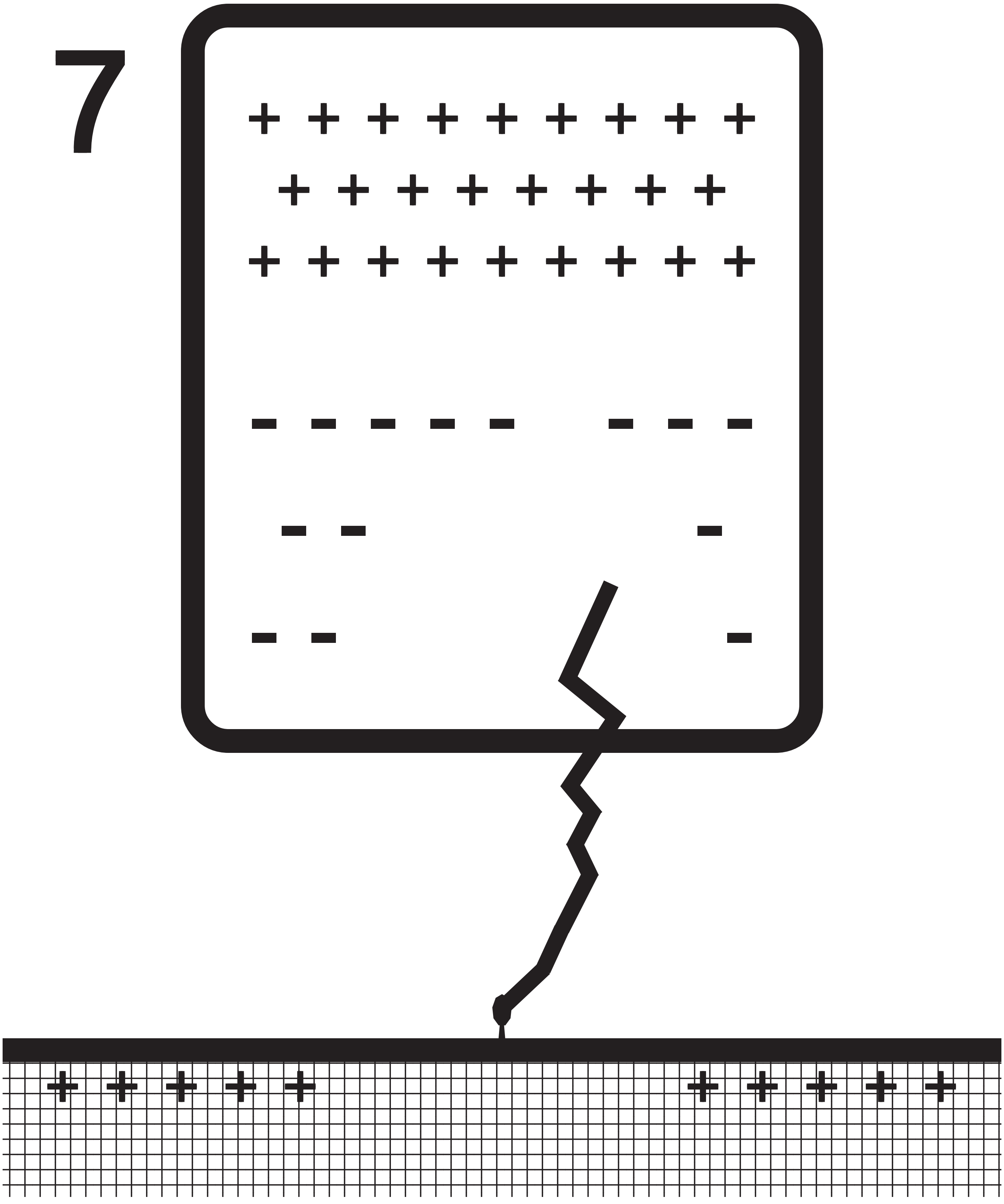


Figure 40: Formation of a negative cloud to ground lightning strike -- second stroke exchnage. (Rakov & Uman 2003)

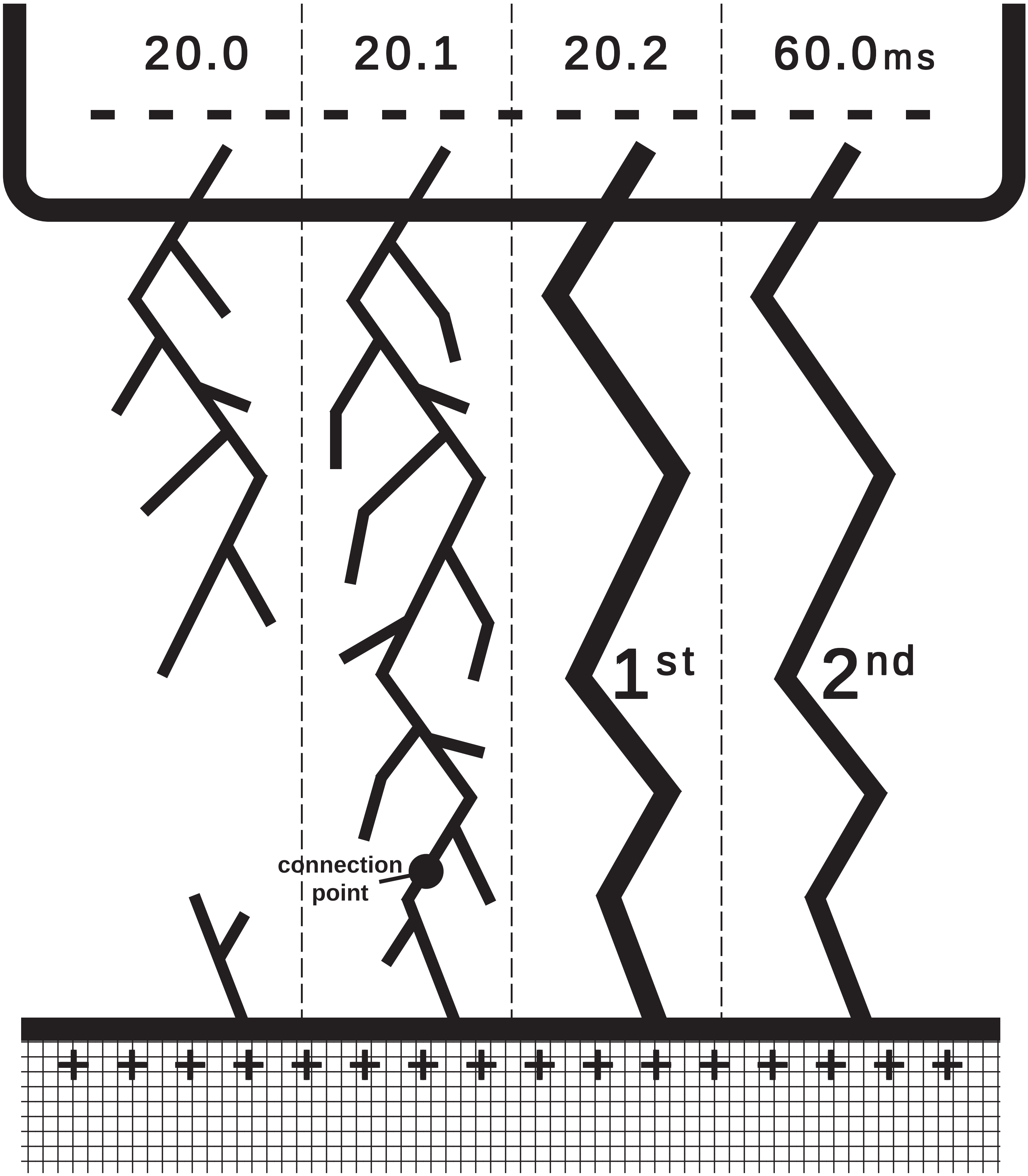


Figure 41: Timing in milliseconds of fist and second negative cloud to ground lightning strokes from start in cloud.
(Rakov & Uman 2003)

Cloud Leaders

Most lightning begins as near invisible fingers of negative charge pushing downward from near the base of storm clouds. The bottom portion of the cloud has collected a large negative charge field potential. Because positive and negative charges attract, there is a positive charge field potential that swells below the cloud base on the ground and follows along across the landscape beneath a storm. This effect can be visualized as a charge wave flowing across the landscape below storm clouds.

Fingers of negative charge potential pushing out below a cloud base are called "cloud leaders." Cloud leaders rapidly stretch downward through the air following a pathway of least electrical resistance. Precipitation, other lightning paths, and even cosmic rays help determine the path cloud leaders descend. (Uman 1971,1987). The leader jumps forward in ~150 feet segments. (Uman 2008). The jagged nature of lightning comes from the zig-zag pathway followed by the near invisible cloud leaders rapidly pushing downward toward the ground. Cloud leaders push out toward the ground at 450,000 miles per hour. Each leader step produces visible light, radio waves, and x-rays. (Uman 2008). Some cloud leaders are always pushing downward below a cloud base. Figure 42.

Ground Streamers

Enhanced field effects concentrated along the Earth's surface below storm clouds, are pulled (or stream) upward toward the negative cloud charge. These positive charges streaming off the top of tall structures are called "ground streamers." These streamers can be thought of as flowing up and off the top of tall topographic features and structures like trees. Ground streamers are a simple construct to explain the ground field enhancement which occurs around and over tall ground structures. (Rakov & Uman 2003)

Ground charges mount up in a standing wave following the storm base over the landscape. Over the top of tall structures (taller than neighboring objects) ground steamers present an enhanced positive charge field available for connection with negative charged cloud leaders. Trees and other tall structures provide ground attachment points for ground streamers.

Figure 43 shows an open field, fair weather (normal) electrical field through the atmosphere down to the ground. The dotted equal voltage lines allow charge flow evenly to the ground as shown with the solid lines. Figure 44 represents how an electrical field is enhanced or intensified by tall ground objects. In this figure, equal voltage lines (dotted lines) are concentrated above and around the ground object and the charge flows are curved toward the object. Anywhere the dotted voltage lines are closely stacked, the electrical field is enhanced and atmospheric charge flow will be concentrated on and around the object.

Hair Raising

Until a charge exchange channel is connected / opened, little can be seen of the lightning initiation process. The events leading to lightning occur over extremely short time intervals. Some people have experienced the unnerving sensation of being part of an enhanced charge field under storm clouds. Various reactions and sensations have been cited from being within a ground charge wave. Observers in fire towers know the feeling of being near a strong ground steamer as storms pass over.

Connections

Long cloud leaders push downward from the cloud base and short ground streamers flow upward off tall objects. As a cloud leader approaches the ground, it connects with a ground streamer. An electrical connection between a cloud leader and a ground streamer occurs about 100 - 1,000 feet above the ground surface or above the tip of a structure, depending upon current load. The charge exchange path is now open and charges are rapidly exchanged. The charge difference between cloud and ground is temporarily neutralized. The massive electrical charge exchange generates light (both visible and unseen wavelengths) we see as lightning.

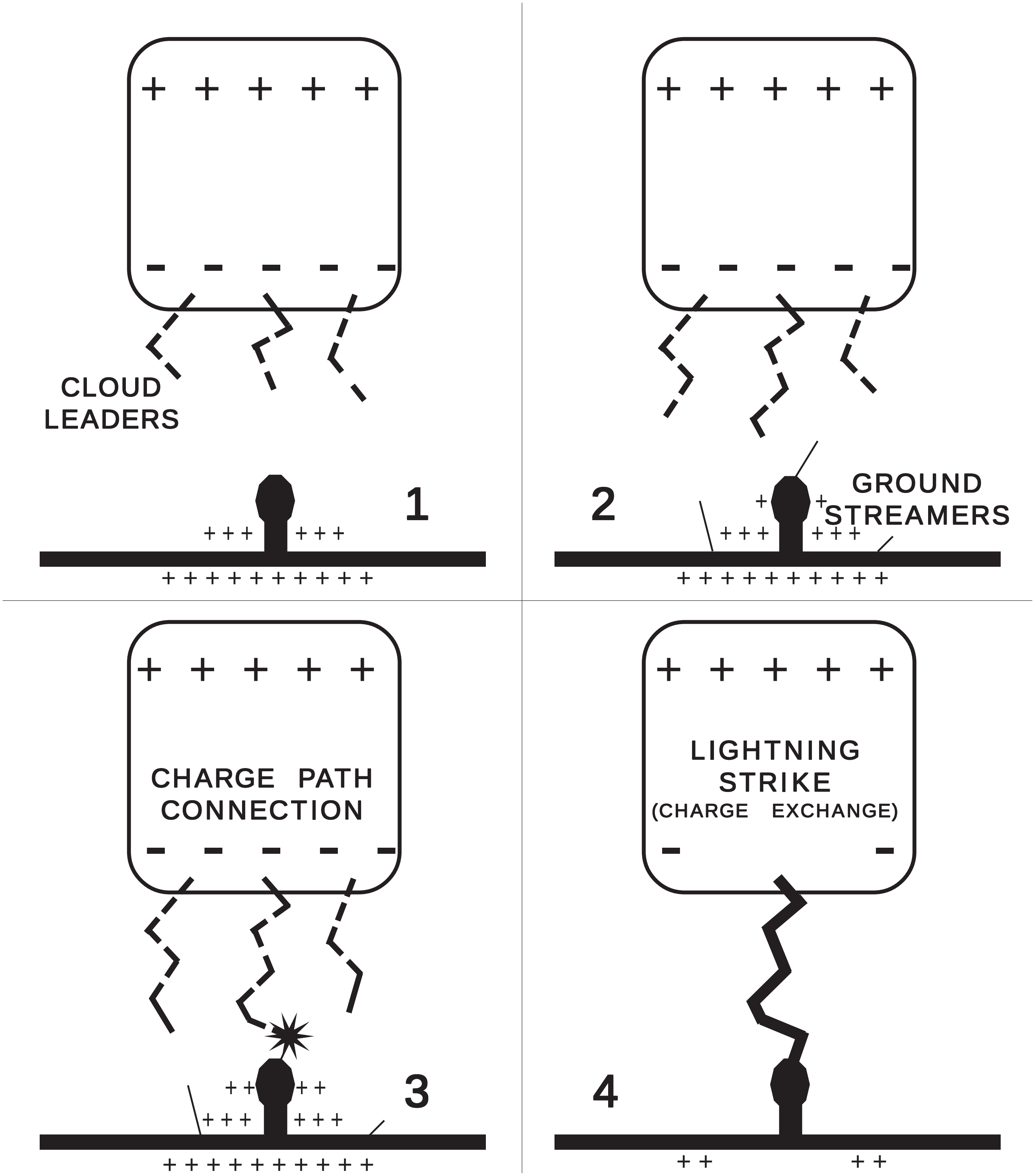


Figure 42: Components of lightning strike with negative polarity: 1) cloud leaders; 2) ground streamers; 3) connection of charge exchange pathway; and, 4) massive charge exchange and light emission. (Uman 1987)

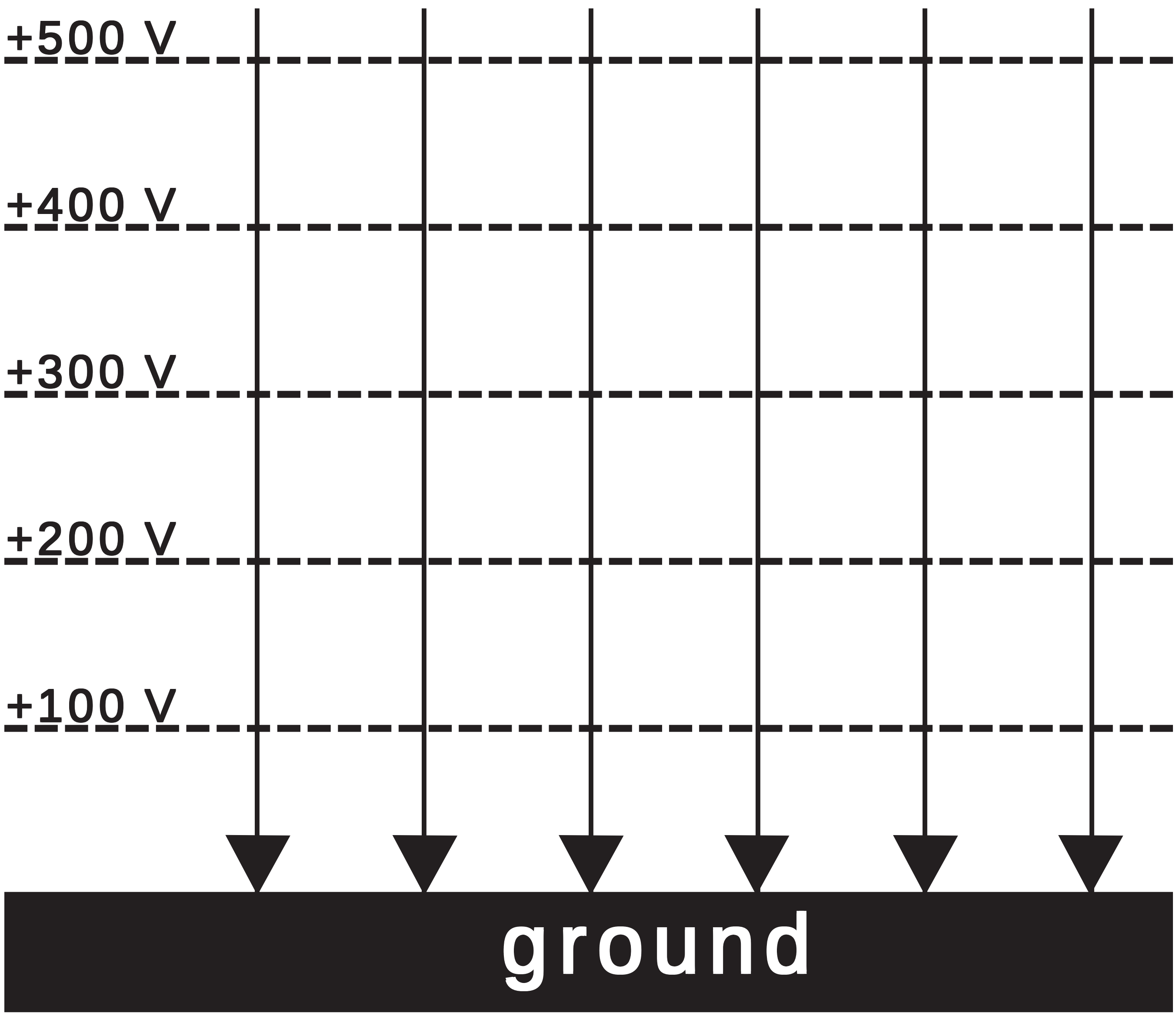


Figure 43: Fair-weather electric field over ground.
(Bouquegneau & Rakov 2010)

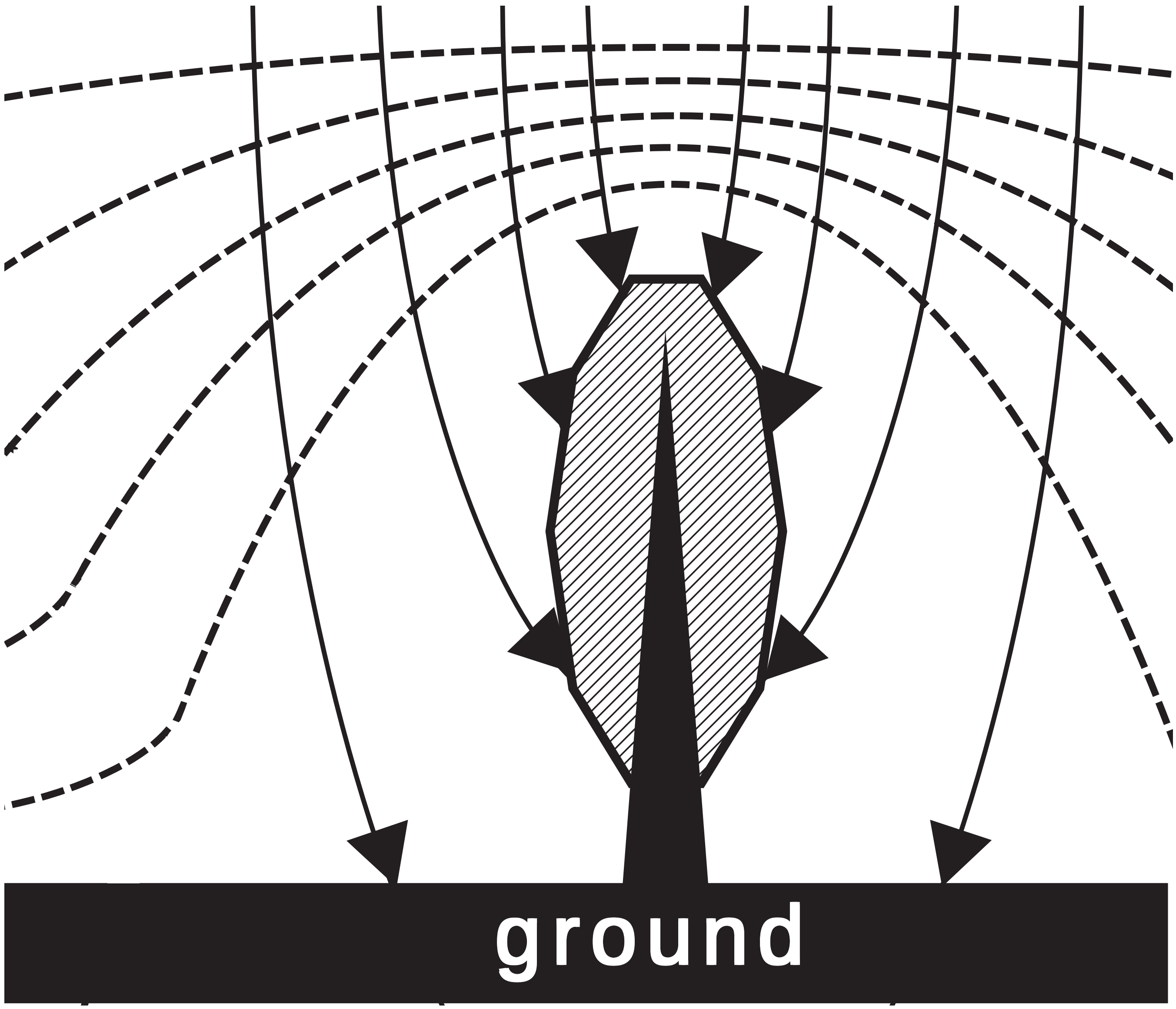


Figure 44: Electric field enhanced by ground structure.
(after Bouquegneau & Rakov 2010)

Charge Channel

When charge paths connect, a visible stroke moves in the charge channel at 1/3 the speed of light, spewing light and instantaneously heating air. Usually several strokes, or charge exchanges, occur in one complete lightning strike to neutralize charge differences. Because of rapid changes in air resistance, wind movement of ionized air, and the strongest ground streamer location, various strokes in one lightning strike may not follow the same pathway. Several trees in a row may show damage from different strokes following different paths within one lightning strike. Some trees have been struck a number of times. The ground streamer characteristics connecting the first strike (or first stroke) can facilitate additional exchanges. (Uman 1971,1987)

Multiple Strokes

Many lightning strikes contain multiple strokes. Figure 45 provides attributes of these multiple strokes for negative and positive lightning. Both the average number of strokes, maximum number of strokes, and interval between strokes are significantly different between negative and positive lightning. The maximum number of strokes in negative lightning would show a decreasing current exchange with each stroke.

The multiple strokes within one lightning strike do not necessarily follow the same path and connect / terminate at the same point on the ground. The distance in miles between different strokes within the same lightning strike is given in Figure 46. Stroke separation can be as much as 5 miles, and averages ~2 miles apart in the same lightning strike.

Forks

One research topic in need of further study, and not easily recorded by instruments, if forked lightning. Forked lightning is defined as a strike with multiple ground termination points. Figure 47 is a summary of forked lightning average attributes. Note almost half of all strikes have multiple termination points separated by as much as 4.5 miles. Some strikes have more than two termination points. Figure 48.

Side Flashes

As the charge exchange channel develops, lightning may jump from the side of tall structures onto adjacent houses or through people. The path of a lightning strike is unpredictable because the strike itself changes local air and material resistances to electrical charge exchange. Each millisecond presents a new potential pathway for electricity flow which could be almost the same as the last pathway, or could be completely different. (Uman 1971,1987)

Being Positive

For positive strikes, charge exchanges occur over greater distances between storm cloud tops and the ground. These positive lightning strikes can be several times more powerful, impact a larger ground area, and last longer than the common negative (polarized) cloud-ground strikes. Tree and tree clump damage can be especially severe when along positive lightning strike paths. Fire ignition is a significant possibility.

Flash

A lightning strike is made up of a number of individual strokes. Each stroke can last many 10's of milliseconds. The duration of a complete flash of lightning, including periods between individual strokes, is usually around one-half second. The human eye can just visualize individual strokes within each strike making lightning appear to flicker.

Negative Ground Strike	
single stroke flashes	~15%
multiple stroke flashes	~85%
average strokes	= 5.5
maximum strokes	= 22
stroke interval	= ~58ms
Positive Ground Strike	
single stroke flashes	~75%
multiple stroke flashes	~25%
maximum strokes	= 3
stroke interval	= ~96ms

Figure 45: Lightning stroke characteristics for positive and negative strikes. (Cooray & Fernando 2010)

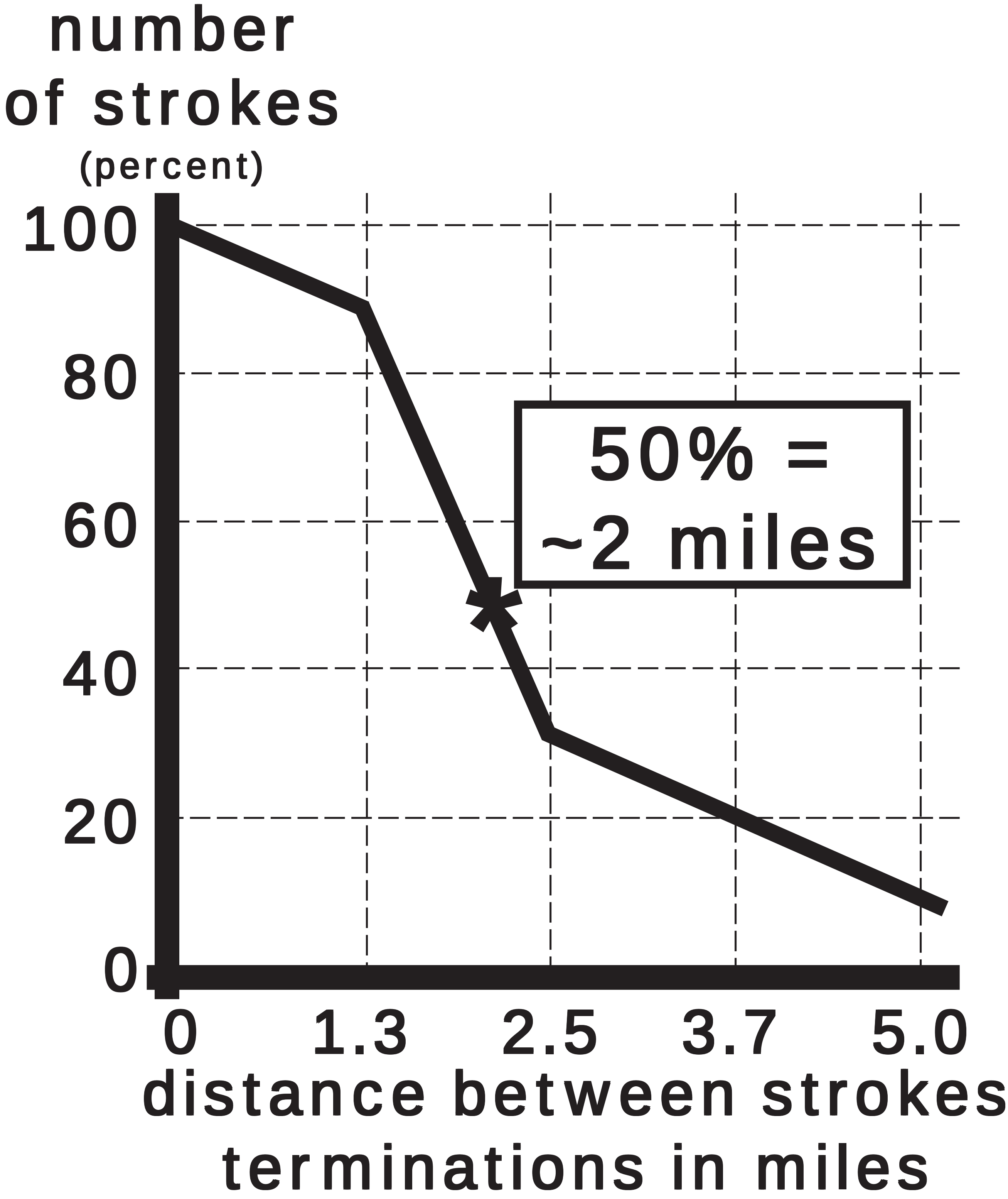


Figure 46: Distance in miles between strokes terminations within the same lightning strike. (Rakov & Uman 2003)

Fork Lightning

lightning with >1 termination point

lightning strikes with multiple termination points = 45%

termination point average separation distance = ~1.05 miles apart

(range = 0.18 to 4.5 miles apart)

Figure 47: General attributes of fork lightning (multiple termination points on the ground). (Cooray & Fernando 2010)

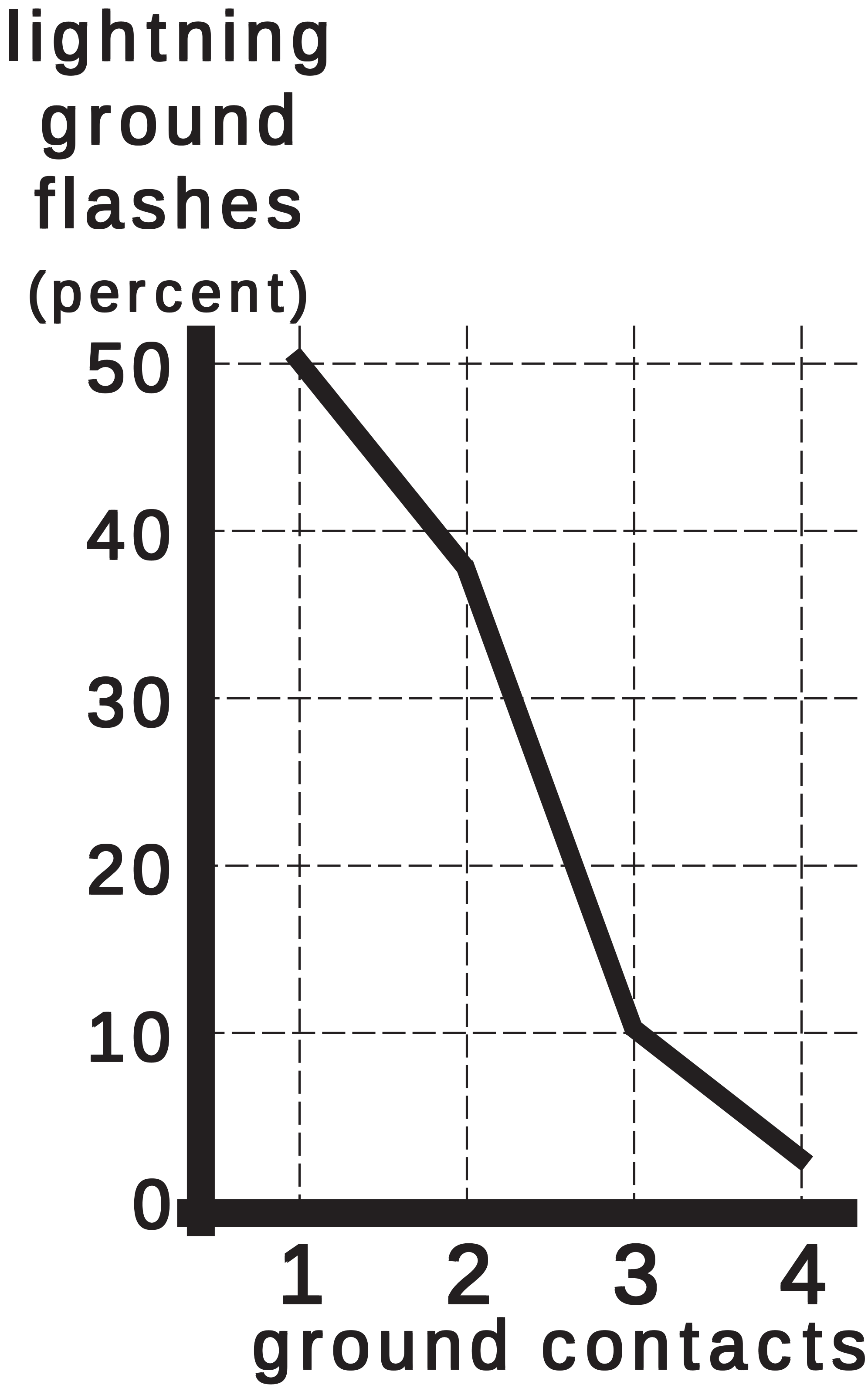


Figure 48: Percent of ground flashes (fork lightning) which generate a given number of multiple ground termination points. (Cooray & Fernando 2010)

Average electrical values for a strike are 100 million volts and 35,000 amps. The lightning strike core ranges from 1/5 to 1/2 inch in diameter surrounded with an ionized, glowing envelope 4-6 inches in diameter, and a bright light corona of 1-5 feet in diameter.

HOT!

The energy liberated by a lightning strike is more than just a current exchange and a bright light arc. The temperature inside the narrow core of the lightning strike can be hotter than the surface of the Sun. Figure 49. (Uman 1971; MacGorman. & Rust 1998) For a lower than average current exchange (20kA over 90 microseconds), core temperature reached 50,000^{o}F dwindling quickly to <1,000^{o}F within an inch of the core. Figure 50.

EXPLOSIVE!

The explosive nature of this almost instanaeous temperature jump can be seen in the amount of pressure generated. The instantaneous heating of air in the lightning core to such extreme temperatures generates a supersonic shockwave (10X the speed of sound) over a short distance. Figure 51 shows the air pressure wave generated by superheating air in the lightning core. Again, in a lower than average current strike (20kA over 90 microseconds), pressure was greater than 24 atmosphere at the core declining to near normal air pressure by 1.5 inches from the core.

Boom

The flash of individual lightning strokes and sound of thunder are generated by the same event. Because light travels faster than sound, the flash is seen first and then thunder is heard. The thunder sound wave (an acoustic wave) is travelling nearly 770 miles per hour at 70^{o}F. If you count the number of seconds between flash and thunder, you can tell how far away the lightning strike occurred. Every second, thunder sound waves move 1/5 of a mile (actually 0.214 mile). For example, if you count 5 seconds (4.7 seconds) between the light flash and thunder, then lightning flash was one mile away. (Uman 1971)

Ground

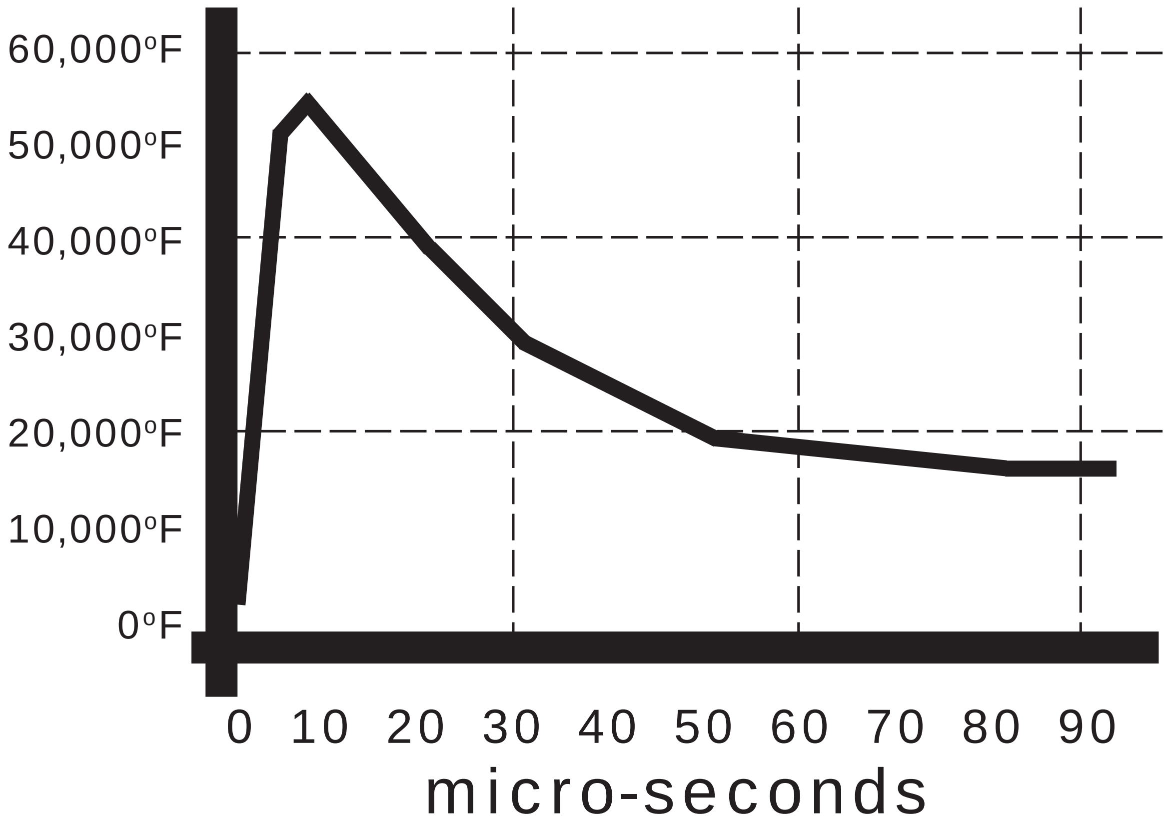
When the charge exchange pathway is opened, energy races into soil and is dissipated across soil surfaces and volumes. Most soils can channel and dissipate large electric charges. The electrical grounding process is comprised of soil water and atmosphere components electronically capturing energy in unoccupied electron shells and within chemical bonds. This energy is converted to heat, temporarily held by various atoms, or permanently associated with higher energy chemical bonds.

Arcing

When lightning strikes a tree, due to massive current exchange, some of the energy generates a surface flash-over or ground arcing. Figure 52. This arcing can radiate out from the ground connection of the strike as much as 65 feet. Most lightning strikes over 15kA will surface arc, especially when soil is completely saturated and without air pore space. This arcing is across the soil surface and is not part of internal soil dissipation. Severe damage to animals / people and surface tree roots can occur.

Lightning Strike Probabilities

Risk assessment processes for when and where trees could be struck by lightning are complex. Examining probabilities for any one tree within a charge exchange path requires a set of assumptions, most derived from research on free-standing communication towers. The lightning strike probability formula used here is from



(1 micro-second = 0.000,001 second)

Figure 49: Lightning core temperature in degrees Fahrenheit (ºF) over time in micro-seconds (millionth of a second).
(Few 1995; MacGorman. & Rust 1998; Uman 1971,1987)

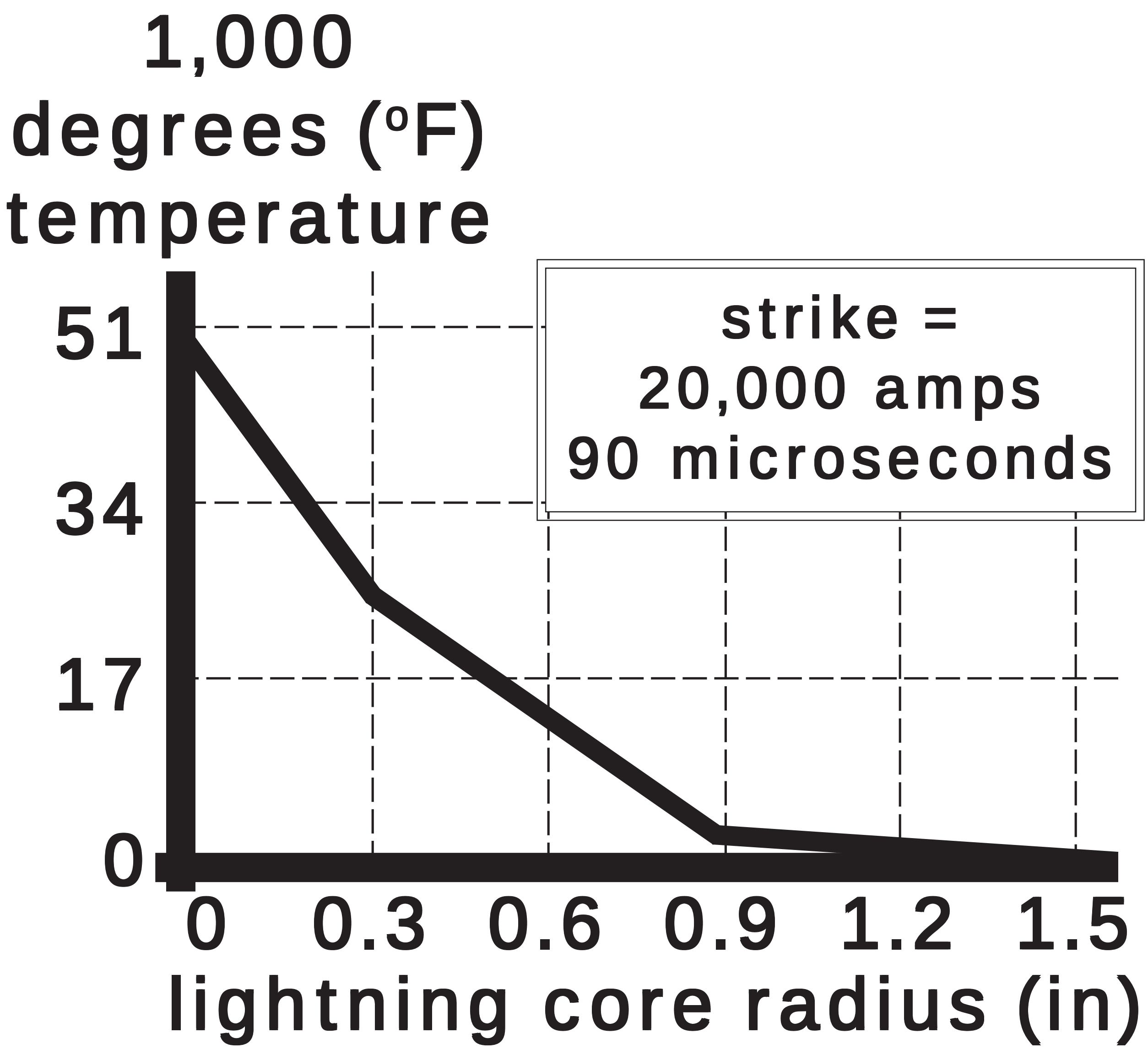


Figure 50: Temperature of lightning strike core away from its center. (derived from Rakov & Uman 2003)

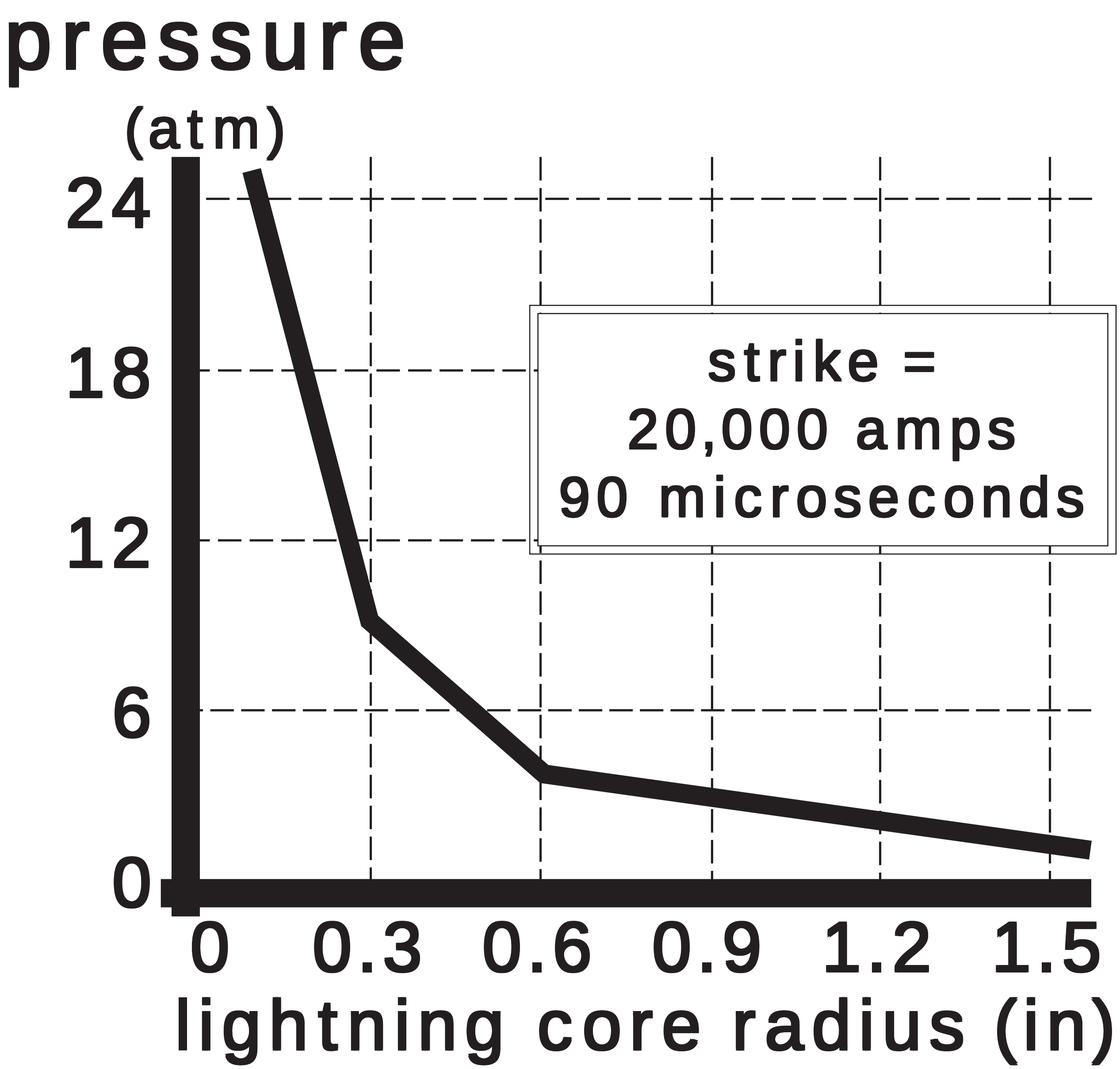


Figure 51: Pressure around lightning strike core moving away from its center. (derived from Rakov & Uman 2003)

Surface Flash Over / Arcing (maxiumum distance = 65ft)

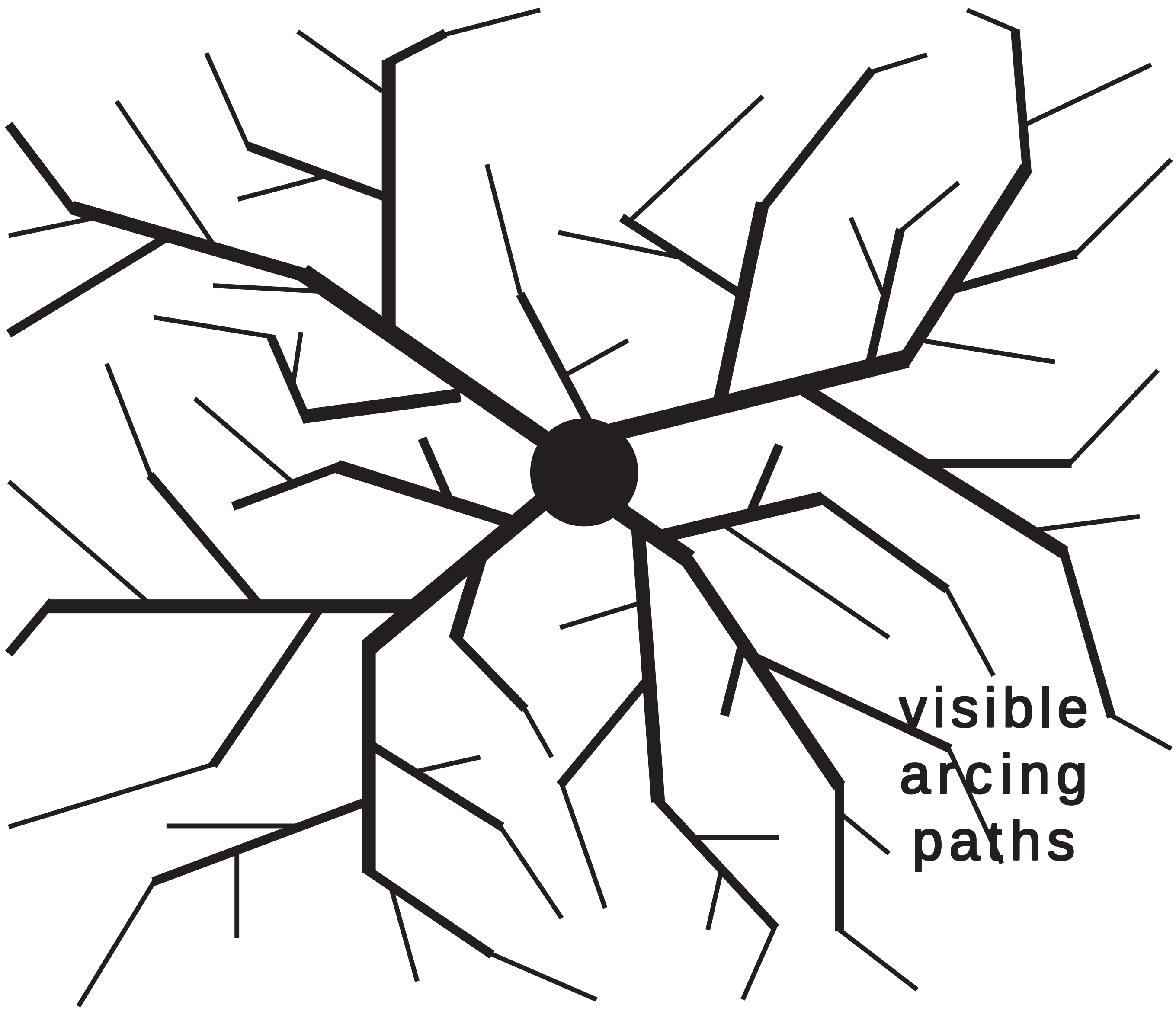


Figure 52: Diagramatic view from above of tree stem base (dark circle in middle above) struck by lightning. Most lightning strikes with peak current over 15kA, especially under wet / rainy conditions, arc across soil surface.

(Cooray & Fernando 2010)

Bazelyan & Raizer (2000). In most simple terms, a lightning ground strike probability is dependent upon historic lightning strikes in the area, height of a tree, and the presence of any surrounding tall objects.

Figure 53 provides the historic number of lightning strikes per square mile per year expected for the Southeastern United States -- a lightning strike density map. Lightning strike density maps are available for most areas on Earth and can be used to generate lightning strike probabilities. Figure 54 is a list of the number of years between lightning strikes on a single tree growing at a given height above its surroundings under a specific lightning strike density. The formula used to determine strike probabilities is:

$$\text{Number of Years Between Lightning Strikes} = \frac{1}{(\text{ N mile}^2 \text{ per year }) \text{ X } \{[(3.142) \text{ X } ((\text{HT feet}) \text{ X } (3))^2] \ / \ (5{,}280)^2 \}}$$

N mile^2 per year = Number of ground strikes per square mile per year.
HT feet = Tree height in feet above its surroundings.

The annual probability of a tree lightning strike is given by the following formula, the inverse (1/X) of the number of years between lightning strikes given above:

$$\text{Annual Probability of a Lightning Strike} =$$

$$(\text{ N mile}^2 \text{ per year }) \text{ X } \{[(3.142) \text{ X } ((\text{HT feet}) \text{ X } (3))^2] \ / \ (5{,}280)^2 \}$$

N mile^2 per year = Number of ground strikes per square mile per year.
HT feet = Tree height in feet above its surroundings.

Note figure values in years have been rounded or truncated to provide a whole number. These calculated values can be used to estimated how many years (X) between lightning strikes for a single isolated tree in a flat area, or for a given tree height above its surroundings. The inverse of this number (1/X) is the annual probability of a strike.

For example, if the number of ground strikes per square mile per year as 15, and the tree height above its surroundings is 60 feet, then the estimated number of years between strikes to the tree would be 18 years. The inverse of 18 is the annual probability of a lightning strike on the tree, or 0.056 (5.6% per year).

Remember strike probabilities are based upon an estimate of lightning attraction by ground field enhancement effects and a highly summarized map of historic lightning ground strike data. These values are intended to help tree health care providers understand lightning strike probabilities on trees of various heights above their surroundings. These probabilities are a rough estimate of dynamic natural events. Use of this information can assist tree health professionals decide if lightning protection systems would be appropriate and cost-effective for a tree in a given position in a landscape.

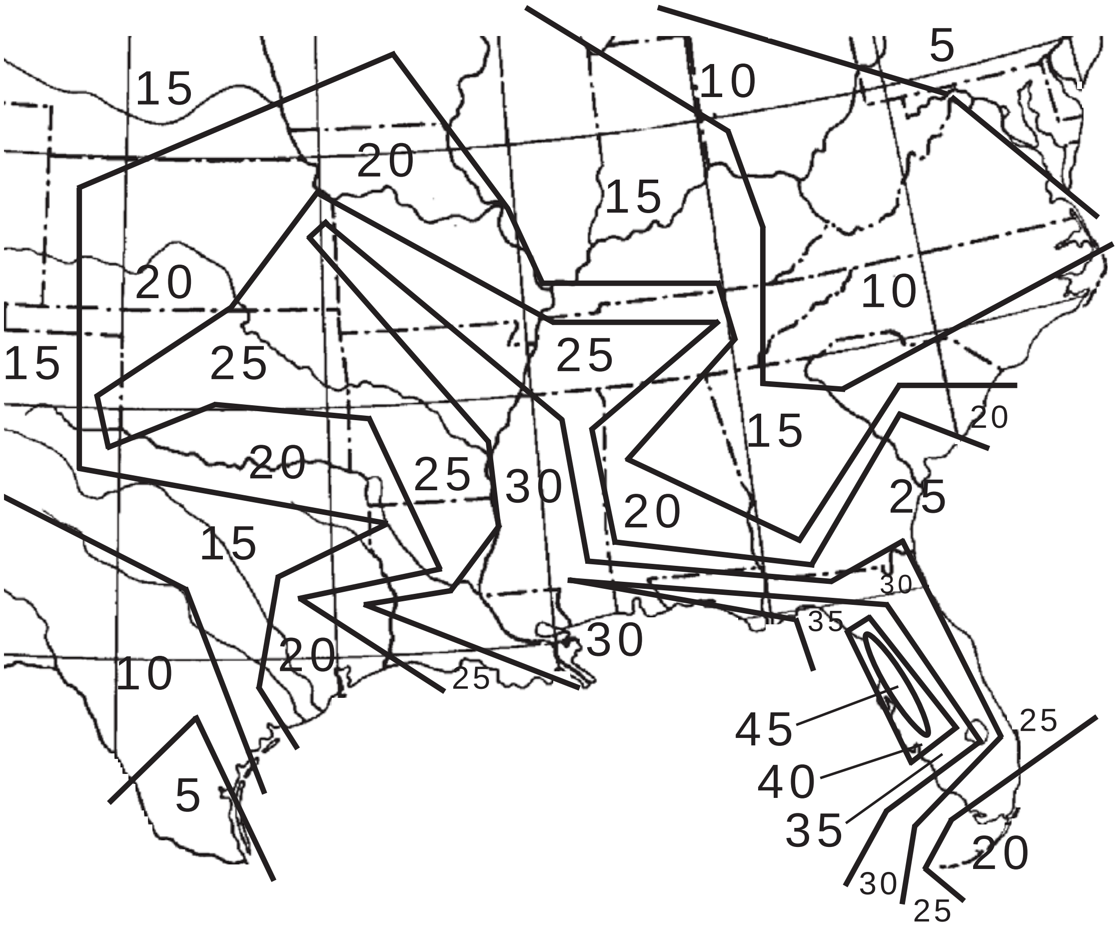


Figure 53: Average historic number of lightning strikes (clound to ground strikes) per square mile per year for the Southeastern United States.

YEARS BETWEEN STRIKES

tree height (feet)	lightning strikes per square mile per year									
	2	5	10	15	20	25	30	35	40	45
5 ft	9,999	8,000	4,000	2,500	2,000	1,500	1,300	1,100	1,000	900
10	5,000	2,000	1,000	650	500	394	328	281	246	219
20	1,200	500	246	164	123	98	82	70	61	54
30	550	219	109	73	54	43	36	31	27	24
40	308	123	61	41	30	24	20	17	15	13
50	197	78	39	26	19	15	13	11	9	8
60	136	54	27	18	13	10	9	7	6	6
70	100	40	20	13	10	8	6	5	5	4
80	77	30	15	10	7	6	5	4	3	3
90	60	24	12	8	6	4	4	3	3	2
100	49	19	9	6	4	3	3	2	2	2
120	34	13	6	4	3	2	2	1	1	1 yrs

Figure 54: Estimated number of years between a single l ightning strike (ground strike) impacting a tree of a given height (in feet) standing by itself (i.e. no trees or structures within three tree heights in any direction), or for a tree of a given height above its surroundings, in an area with a specified historic lightning ground strike count per square mile per year. (Bazelyan & Raizer 2000)

Strike Distances

To better understand why lightning strikes one tree and not another requires an appreciation of lightning attraction or strike distances. There are many ways to determine strike distances. The two critical features of estimating lightning strike distances are current level of charge exchange and tree height. The purpose of examining strike distances is to estimate lightning strike probability areas around a tree. The methods used to calculate lightning strike distances all change the probability of a strike.

The lightning striking distance measure is shown in Figure 55. It represent not the final jump between ground streamers and cloud leaders, but the distance between a cloud leader and the origination source of the ground streamer. Figure 56 shows the lightning strike distance above a tree. Remember the striking distance is increased above a tree due to its enhanced electrical field compared with a flat soil surface. To calculate the lightning striking distance, Figure 57 presents a graph of striking distance in feet per peak lightning current in kA. The specific formula for the graph is provided.

Another formula for striking distance is given in Figure 58, which shows the general formula and averaged input coefficients from six different examinations. (Uman 2008). Figure 59 provides a graphical view of striking distance showing the wide range of potential values found by different research groups. Note the distance values are in meters. (Uman 2008).

Current Loads

Figure 60 provides the probabilities for three types of lightning strikes occurring with different currents. The three lightning descriptions shown are: 1) a negative polarity first stroke; 2) followed by multiple (average of three to four) negative polarity secondary strokes; and, 3) a positive polarity single stroke (usually with no secondary strokes).

For example, a single cloud/ground charge exchange of positive polarity has a 20% chance of carrying 100,000 amps. A more common negative polarity first stroke has a 20% chance of carrying 60,000 amps, with secondary strokes having a 20% chance of carrying 20,000 amps. Common first stroke lightning averages about 35,000 amps. It is possible, though highly unlikely, to have a charge exchange approaching 300,000 amps. Note the large differences in current between lightning types shown.

Four Methods

There are four common methods of gauging lightning attraction distances. These attraction distance models are called the "Golde current" method, the "double height" calculation, the "equidistance process," and the "electromagnetic process."

The Golde current method (Golde 1977) of determining lightning attraction distance uses only current of the lightning strike. The other three lightning attraction distance formula use tree height, and so are better suited for this manual. The Golde current method for determining lightning strike distances uses the formula:

$$\text{Lightning Attraction Distance in feet} = 32.8 \text{ X } (\text{ lightning current in kA })^{0.65}$$

The double height calculation method can be used for short structures like trees to gauge lightning attraction distances. Tree height in feet is simply doubled (2X tree height) resulting in the attraction distance. This calculation method is seldom used except for rough site estimates. (Rakov & Uman 2003)

The equidistance process also uses tree height in estimating attraction distances. Figure 61 demonstrates tree height multiplied by three (3X tree height) and five times tree height (5X tree height) is the range of lightning strike attraction height. The air distance between 3 and 5 times tree height is where the charge exchange connection is expected to occur in a ground strike. The equidistance process is

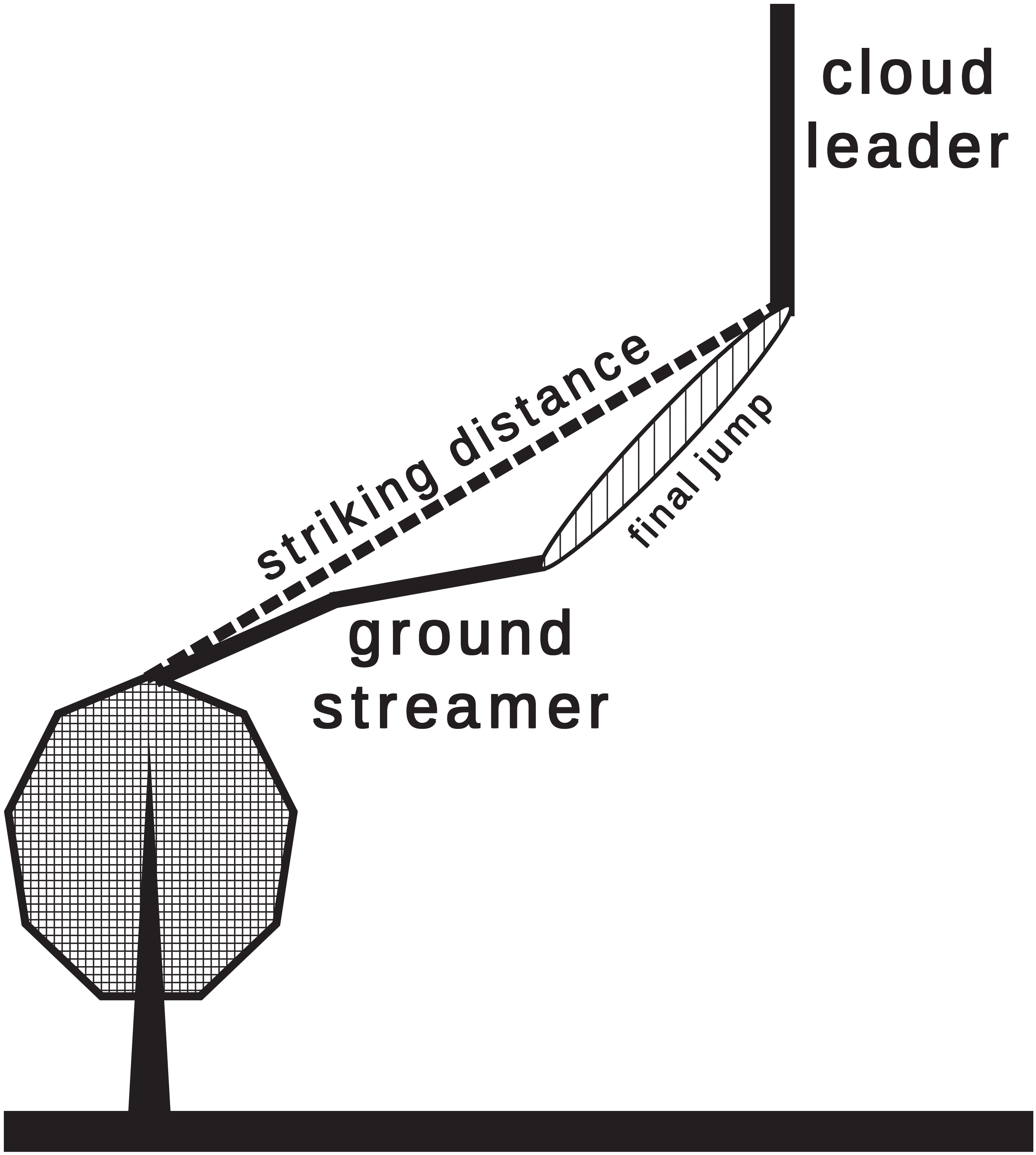


Figure 55: Striking distance definition. (Cooray 2012a)

LIGHTNING STRIKING DISTANCE (SD)

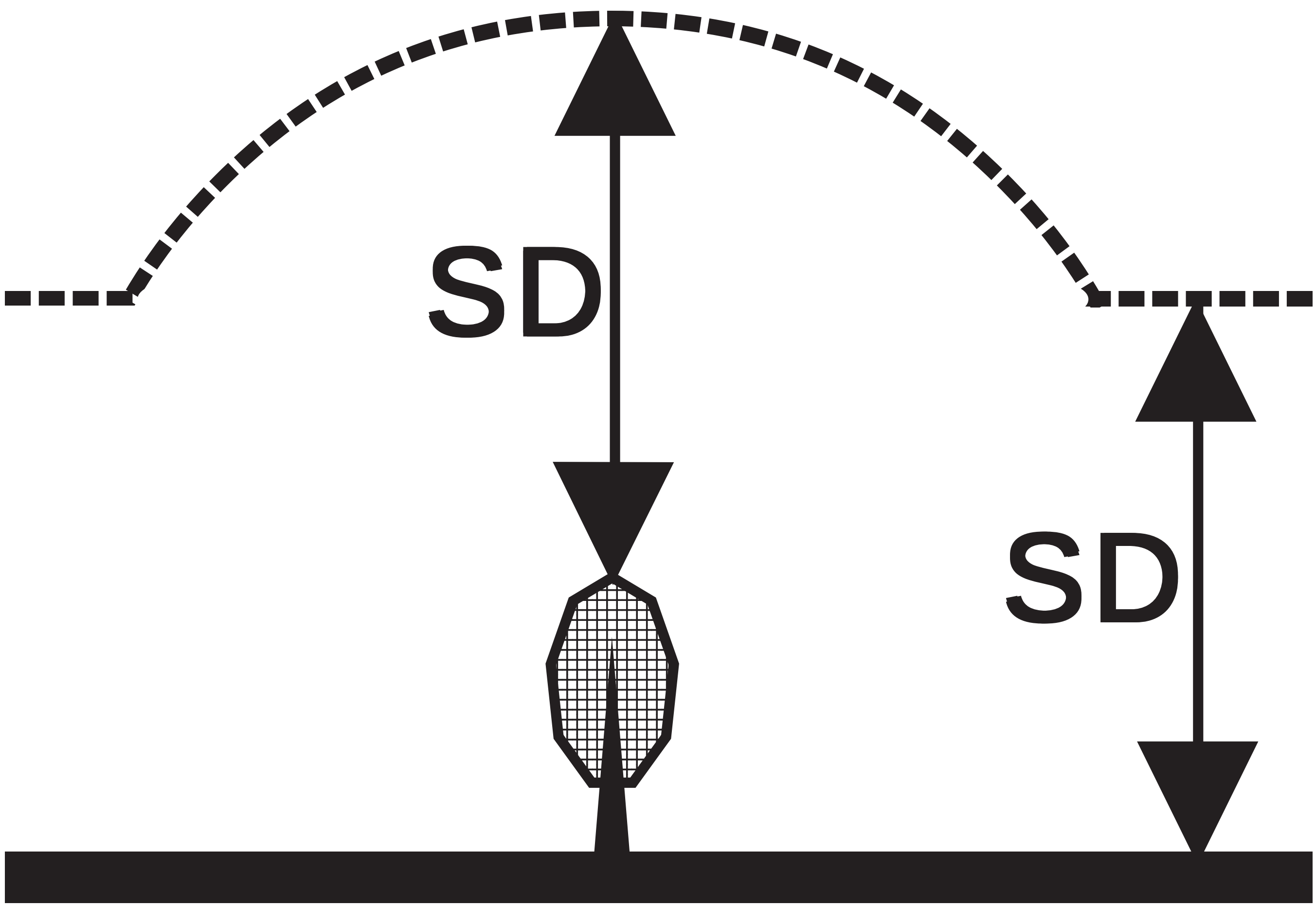


Figure 56: Lightning striking distance for the Earth surface and a tree. (Rakov 2012)

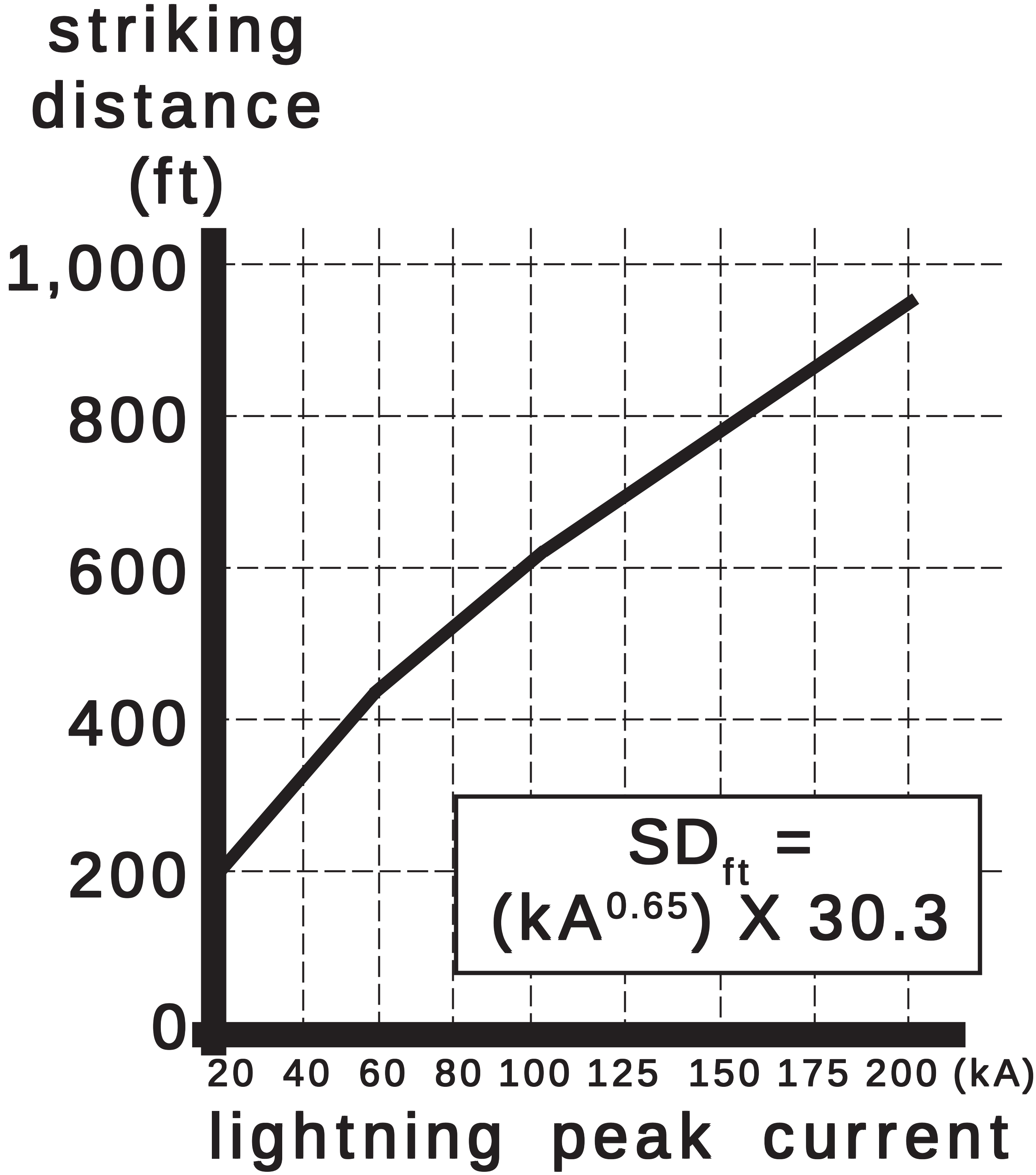


Figure 57: Lightning striking distance in feet for lightning peak current in kA. (Rakov 2012)

Striking Distance (meters) =

$$SD_m = a \times (I_{kA})^b$$

a = 6.5 (range 1.9 - 10)

b = 0.76 (range 0.65 - 0.9)

I_{kA} = first lightning stroke peak current

Figure 58: Standard formulae for striking distance among five coefficient sets. (Uman 2008).

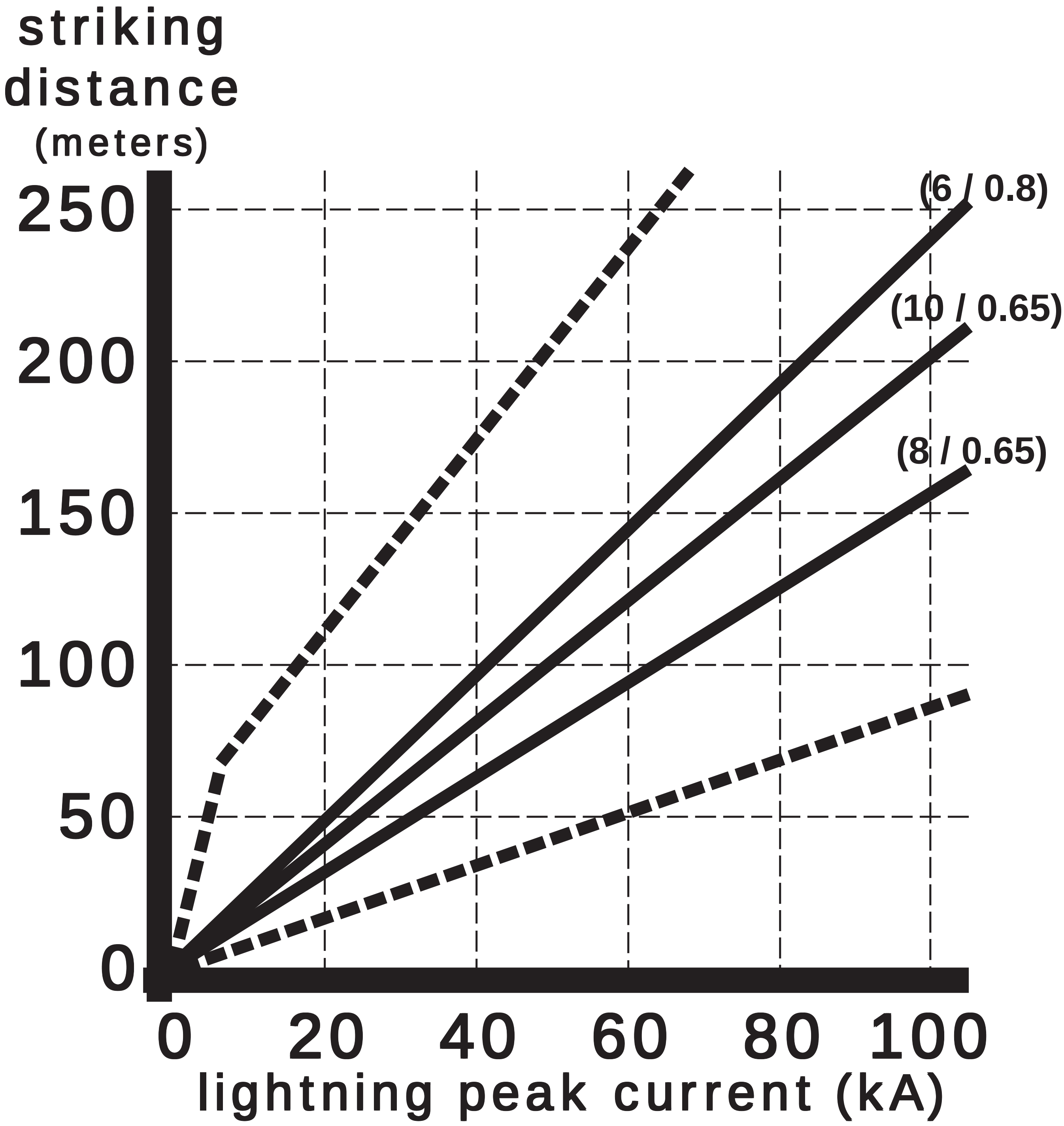


Figure 59: Graphical representation of the wide range of strike distances generated by different research group formulae (*a* / *b* coeffiecents). (Uman 2008)

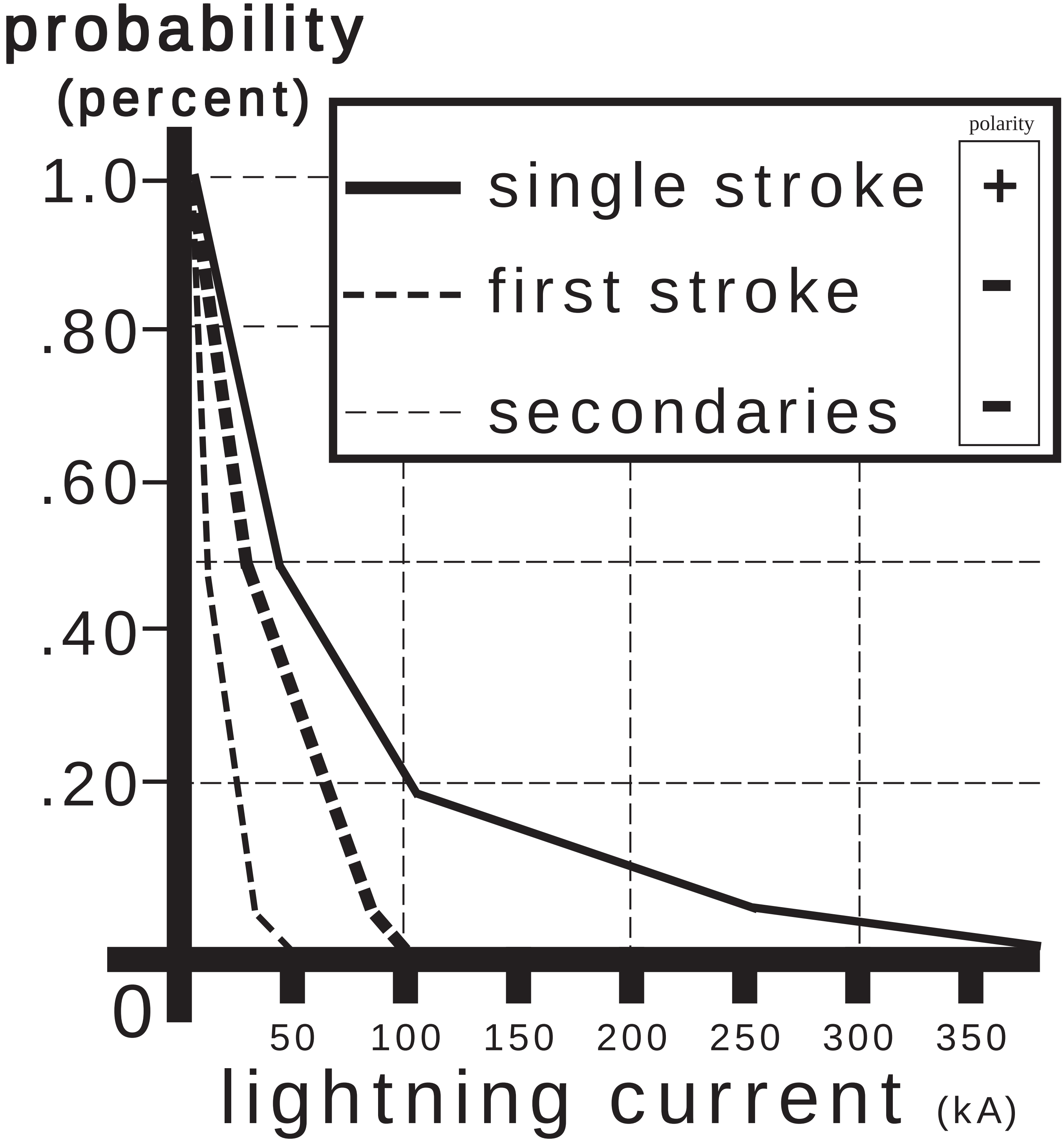


Figure 60: Estimated probabilities for three types of lightning strikes / strokes at various current levels (kA).

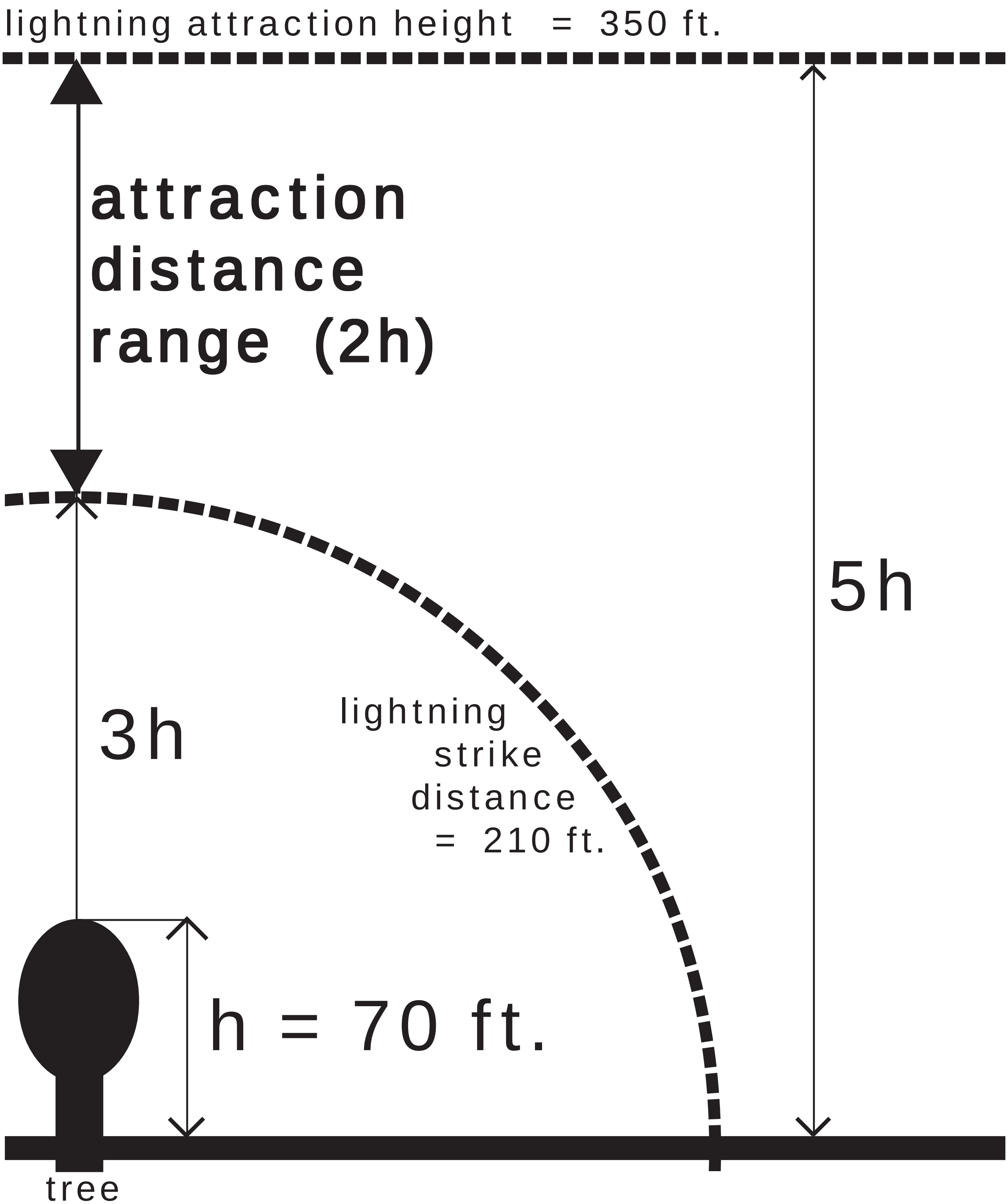


Figure 61: Example lightning attraction distance for a single isolated tree using the equidistance method based upon a tree height (h) of 70 feet.

considered a highly simplified lightning attraction distance estimation and is usually used only for calculating attraction distances for relatively short objects like trees.

Electromagnetic

A more commonly used model for estimating lightning strike distances in trees is called the electromagnetic process. The electromagnetic process, like most of the rest of the striking distance methods, uses lightning current (kA) and tree height as variables. The greater the current, the greater the distance over which lightning can affect and be affected by objects raised above the ground. The electromagnetic model begins with determining the current distance (CD) based on the current contained in an average lightning strike.

Figure 62 presents two different estimates for CD for various lightning current levels, shows an older version which allows CD to level out as current values climb, and a slightly more recent set of CD values which increase at a constant rate (linear). Both data sets are provided to demonstrate the great variability of lightning attraction distances, especially at larger current values.

Figure 63 provides calculated examples of lightning attraction distances using current distances (CD) to project a horizontal attraction distance onto the ground around a tree for several current loads. The formula used is:

$$\text{Lightning Attraction Distance in feet} =$$

$$(((2 \times \text{CD in meters} \times \text{tree ht in meters}) - ((\text{tree ht in meters})^2))^{0.5}) \times 3.28.$$

CD = current distance in meters
'74 = calculation method #1 uses 1974 data for CD.
'67 = calculation method #2 uses 1967 data for CD.

The lightning attraction distance above a tree in this electromagnetic model is about six times the tree height above the ground (6 X tree height in feet). Note under this model the lightning attraction distance above the tree extends a tree height above the general lightning attraction distance of a surrounding flat area.

Figure 64 illustrates the application of values for the electromagnetic model on lightning attraction distances surrounding a 70 feet tall tree (35,000 amp strike, using the 1974 data). Note the height of attraction is greater (420 feet height in this example), but the horizontal radius (202 feet) is smaller than the tree lightning strike distance in the equidistance method (i.e. 3 X tree height all around the tree). Many sources suggest using the electromagnetic process for determining lightning strike distances.

Striking

Figure 65 provides another way of thinking about attraction distance to a tree. In this figure, attraction distance is also tied to tree height over various peak current values. The taller the tree, the more the electrical field is enhanced over a greater distance. In many ways the significant difference between attraction distance and tree height is small.

Figure 66 provides a view of the lightning attraction distance, or the height of electric field enhancement, a tree standing above the landscape provides. The attraction height (striking distance) is dependent upon the peak current of the lightning strike. For a current increase of 29kA, an medium / tall tree attraction height is increased by ~150 feet. The value of this information in tree protection is small, as tree height is not adjustable and the lightning peak current is unknown (except through probability). It is clear tree height does modify the ground electric field.

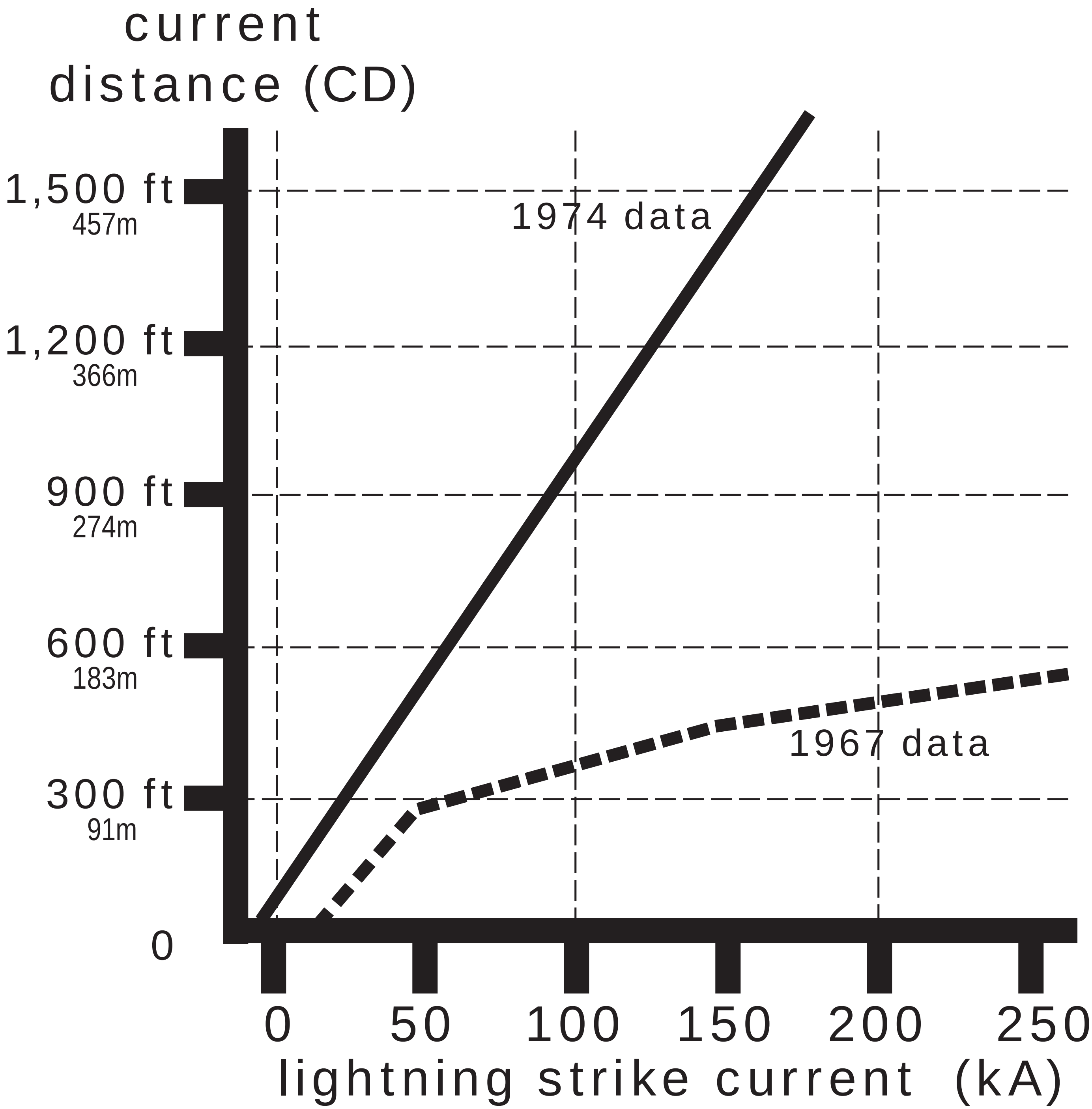


Figure 62: Estimating current distance (CD) in feet based upon lightning current (kA) from two different standard sources. Note current distance is highly variable depending upon the data base used and methodology employed. (from Bazelyan & Raizer 2000.)

tree height (feet)	lightning strike current & analysis year					
	35kA		50kA		100kA	
	'74	'67	'74	'67	'74	'67
20	112	86	138	100	197	115
30	136	104	168	121	240	140
40	156	118	194	139	277	160
50	173	130	215	153	309	178
60	188	141	235	166	337	193
70	202	150	252	178	363	207
80	214	158	268	188	388	220
90	225	165	283	197	410	231
100	235	171	296	205	431	242
120	253	181	321	220	470	260
140	268	188	343	231	505	276ft

Figure 63: Estimated horizontal distance (in feet) away from a tree the lightning strike distance extends from a tree of a given height at several lightning current values for both electromagnetic data sets ('74 & '67).

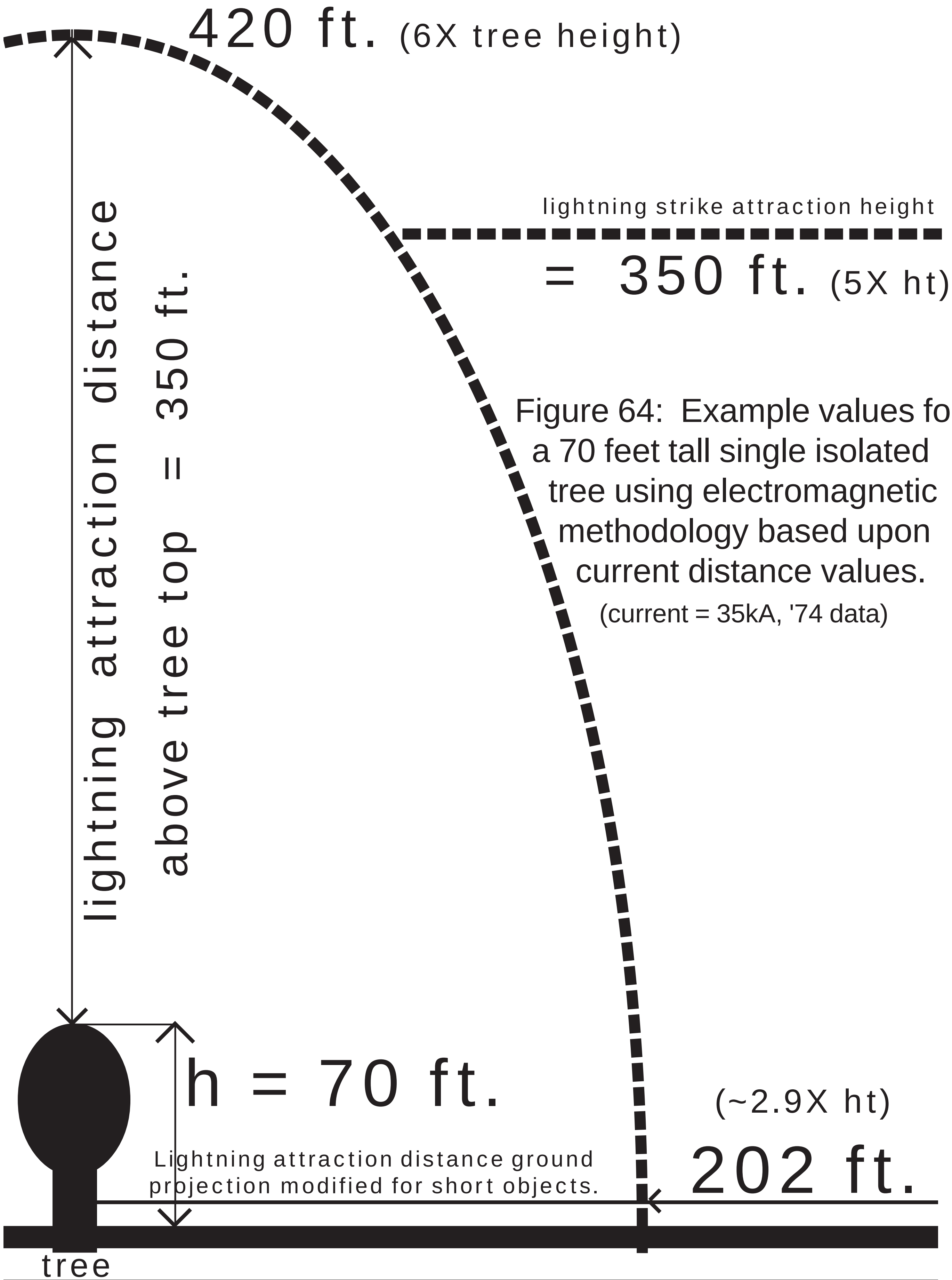


Figure 64: Example values for a 70 feet tall single isolated tree using electromagnetic methodology based upon current distance values.
(current = 35kA, '74 data)

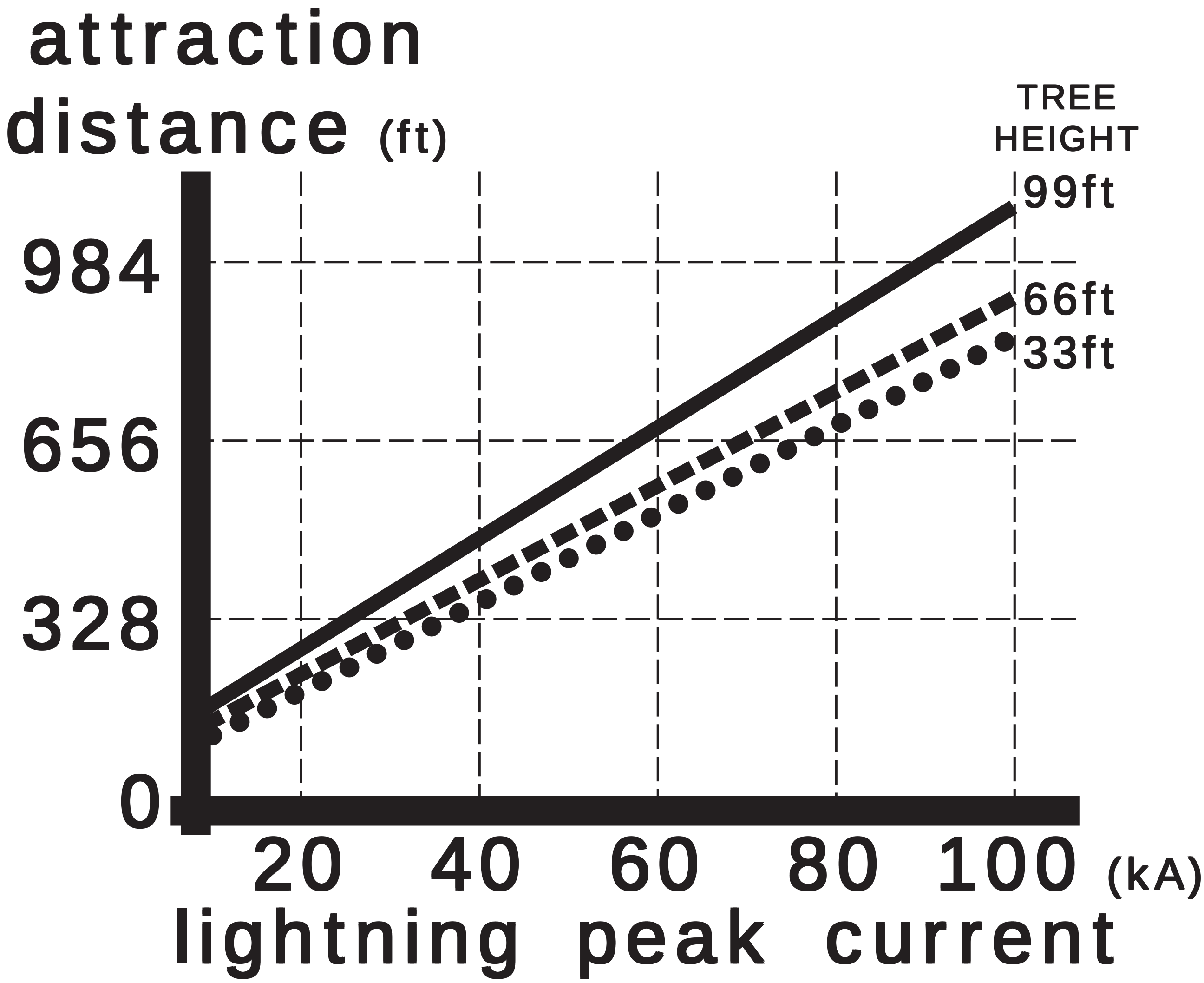


Figure 65: Attraction distance in feet for trees of different heights in feet under various peak currents. (Cooray 2012a)

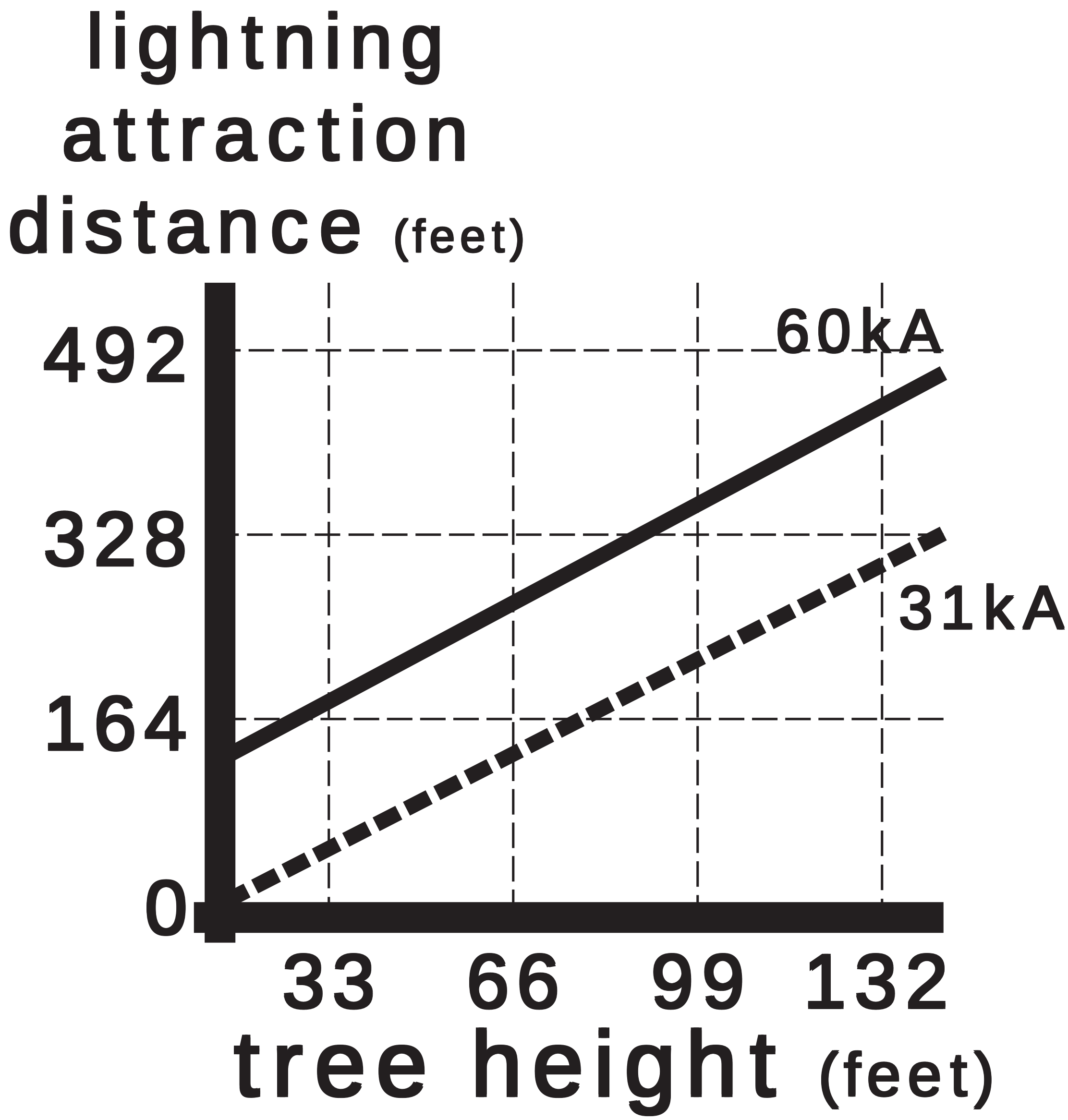


Figure 66: Lightning attraction distance for different tree heights at two peak currents. (Cooray & Becerra 2010)

Figure 67 provides another way of considering how tree height impact the number of lightning strikes for a given strike density. This represents the collection area of a tree, or the enhanced area for lightning strikes based upon added tree height. (Uman 2008). Figure 68 illustrates how the tree collection area is calculated using tree height and crown diameter. Four times (4X) tree height is used traditionally for estimating lightning strikes to trees under 50 feet tall. Six times (6X) tree height is used as an area calculation for international lightning protection standards and trees over 50 feet. Figure 69 shows the lightning strikes per year and number of years between strikes based upon tree height. (Uman 2008).

Years Between Strikes

Figure 70 presents the estimated number of years between strikes to trees of a given height using the electromagnetic model. The formula used is:

Estimated Number of Years Between Lightning Strikes to a Tree =

$$\left[\frac{1}{[\,(3.142)\ \text{X}\ ((((\,2\ \text{X}\ \text{CDm}\ \text{X}\ \text{tree ht m}) - ((\text{tree ht m})^2\,))^{0.5}\,)\ \text{X}\ 3.28)^2\,]\ /\ (5280)^2} \right] \text{X}\ \ \text{HS}$$

CDm = current distance in meters.
'74 = calculation method #1 using 1974 data for CD.
'67 = calculation method #2 using 1967 data for CD.
HS = historic lightning strikes per square mile per year.

For example, a 70 feet tall, single isolated tree, assuming a 35,000 amp lightning strike, using the 1974 data for current distance (CD), and in an area where the number of ground strikes per square mile per year is 15, would be expected to be struck once every 14 years (7.1% chance per year). This probability value is slightly larger than earlier ones where lightning current values were not considered.

Ground Voltages

When lightning strikes a tree, the grounding (earthing) volume beneath the tree canopy in soil is proportional to the energy of a strike. The current surge during a lightning strike to soil volume around a tree base can be large for a relatively long distance away from a tree. Figure 71. This energy surge has human and animal health, first aid, and tree root consequences. The most common injury to humans and animals near a lightning strike (but not directly part of the strike channel) is an induced current through the legs because of voltage differences between ground contacts (feet). Figure 72 demonstrates voltage changes away from a lightning struck tree and its potential to flow through connected ground contact points (i.e. step voltage).

To calculate voltage at the ground surface moving away from a tree lightning strike, the following formula can be used: (from Bazelyan & Raizer, 2000)

Voltage Change Along the Ground Away from a Tree Lightning Strike =

$$[(\,\text{kA}\ \text{X}\ \text{soil resistance in ohms}\,)\ /\ (6.283)]\quad \text{X}\quad [(1\ /\ \text{D}) - (1\ /\ (\text{D} + \text{Sep})]^2$$

Collection Area of Tree =
CA in square miles =

$$\frac{((\text{tree height}_{ft} \times Z) + \text{crown diameter}_{ft})^2}{35{,}514{,}000.}$$

Z = 4 (traditional value & trees <50ft)
Z = 6 (international standards & trees >50ft)

$$CA_{sq.mi.} \times N_{sq.mi.\ per\ year} =$$

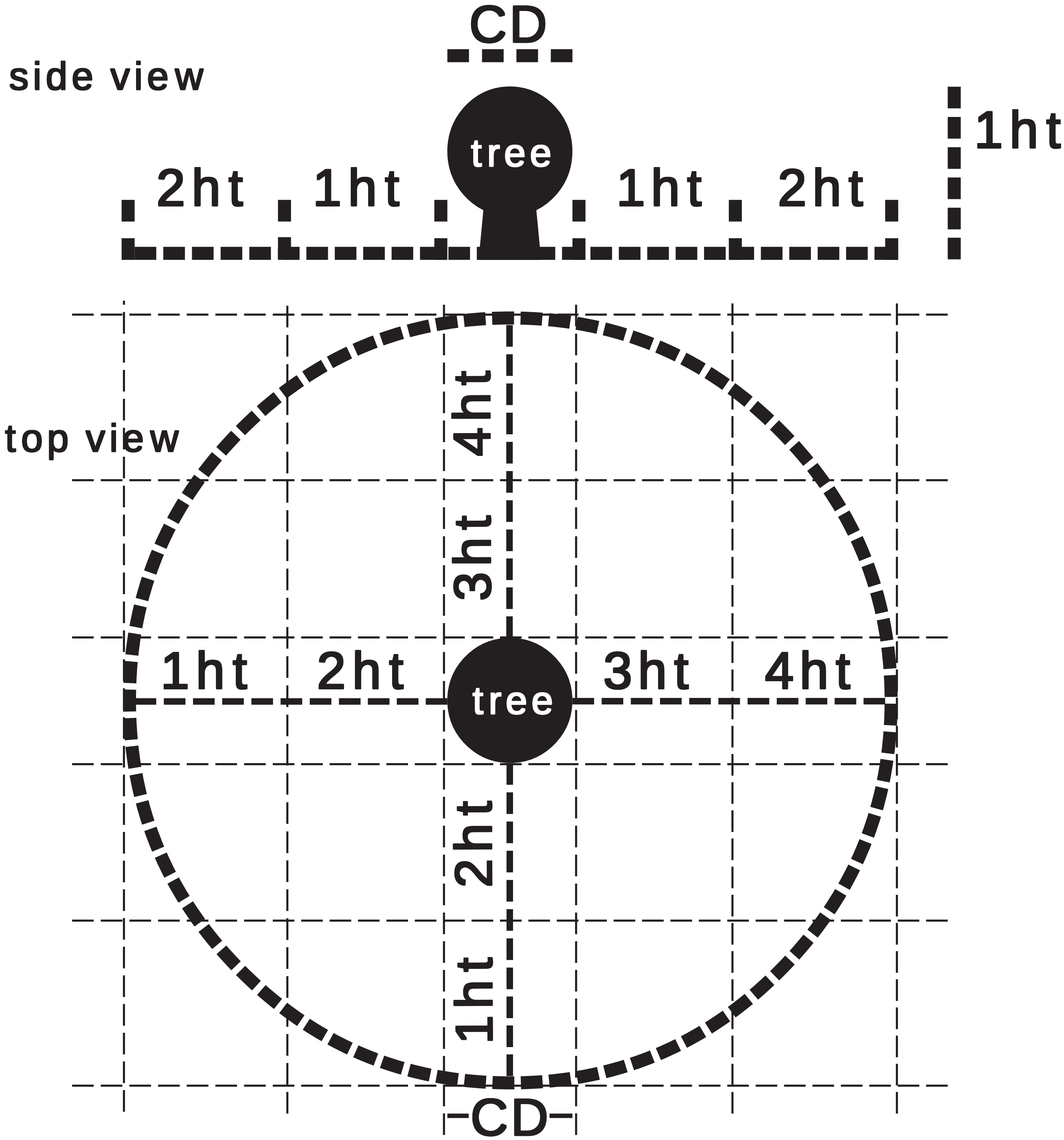
tree strikes per year.

N = annual number of lightning strikes per $mile^2$

1 / tree strikes per year =

years between tree strikes.

Figure 67: Tree collection area for calculating number of lightning strikes to trees of different heights.
(derived from Uman 2008)



$$(4ht_{ft} + CD_{ft})^2 \ / \ 35{,}514{,}000 = \text{tree collection area}_{\text{sq. miles}}$$

Figure 68: Diagram of tree collection area for determining number of lightning strikes to trees of different heights. Z = 4.

(derived from Uman 2008)

tree height (feet)	number of strikes per year	years between strikes
10	0.002	483
20	0.005	196
30	0.009	105
40	0.015	66
50	0.022	45
60	0.064	16
70	0.086	12
80	0.11	9
90	0.14	7
100	0.17	6
110	0.20	5
120	0.24	4

Figure 69: Tree lightning strikes determined by tree collection area for various tree heights using 15 annual lightning strikes per square mile and crown diameter of 30 feet. (derived from Uman 2008)

tree height (feet)	years between strikes '74	'67
20	46	79
30	31	54
40	24	41
50	19	34
60	16	29
70	14	26
80	12	23
90	11	21
100	10	20
110	9	18
120	9	18
140	8	16 yrs

Figure 70: Estimated number of years between lightning strikes to a tree of a given height using two different data sets. (35kA average strike current & number of historic strikes per square mile per year of 15).

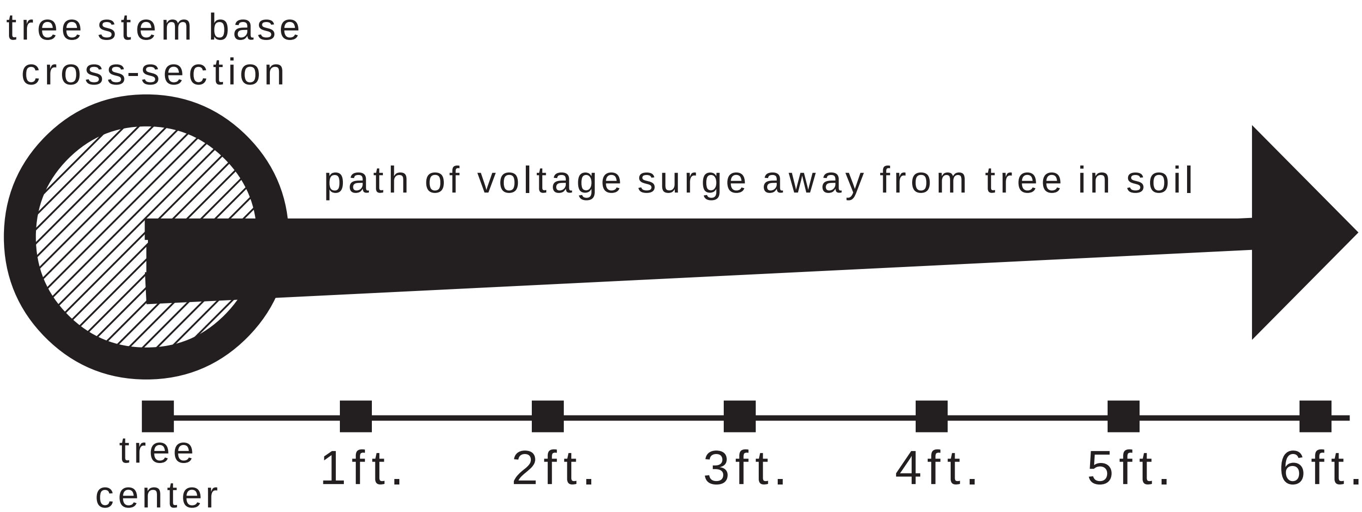


Figure 71: Voltage dissipation in soil away from a tree lightning strike. The perspective is from directly above the tree struck by lightning and its soil surface area along one radial line. The farther from the strike, the smaller the voltage. (Not associated with surface arcing)

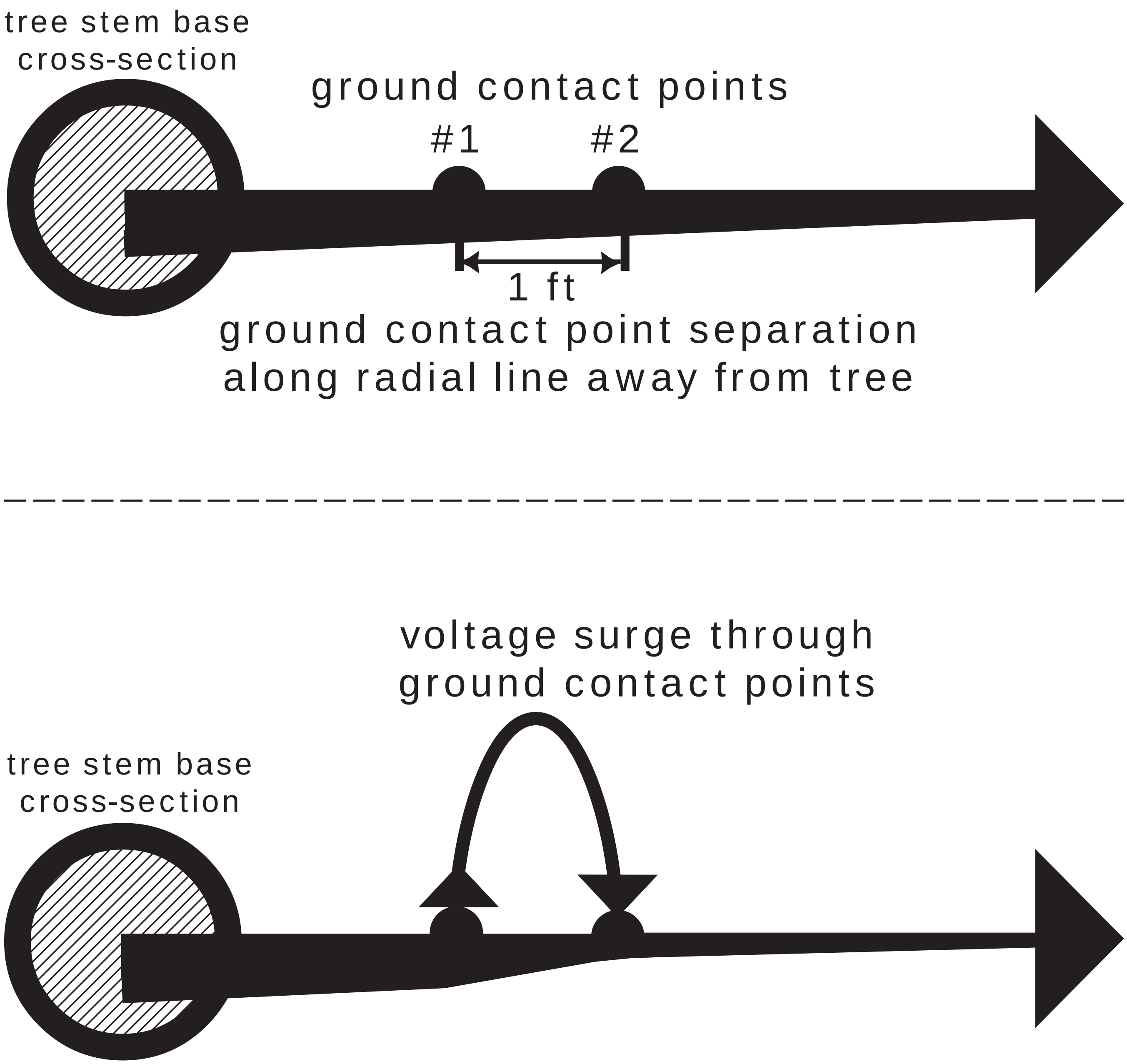


Figure 72: Voltage dissipation in soil away from a tree lightning strike. The farther from the strike, the smaller the voltage. Two ground contact points which are interconnected above ground may have current flowing through them due to the voltage differences at each ground contact point. (Not associated with surface arcing)

kA = current of lightning strike in kiloamps
D = radial distance to strike tree of closest ground contact in feet
Sep = radial distance separating ground contacts in feet

Given the great variability of a lightning strike grounding beneath a tree, no calculated value can accurately represent any strike. Using the formula above, tree health care providers can better understand lightning energy changes once it reaches the ground.

Figure 73 shows the voltage passing between two ground contacts separated by one foot (30,000amp lightning strike and 25ohm soil resistance). For example, the voltage across ground contacts one foot apart at the soil surface, 50 feet from the tree lightning strike, would be approximately 2,000 volts. At 500 feet from the tree lightning strike, the voltage across ground contacts one foot apart at the soil surface would be 240 volts. A person standing with one side toward a tree lightning strike and with feet one foot apart would feel an induced current flow through their legs of 240 volts if they were 500 feet away. This voltage through leg muscles would cause collapse.

2 Or 4 Legs?

Figure 74 provides approximate voltage passing between two ground contacts radially alined with the tree lightning strike and separated by various distances (in feet), at some distance (in feet) away from the tree base. For example, at 5 feet away from the tree lightning strike (30,000amps and 25ohms), ground contacts 3 feet apart would have a voltage difference between them of 22,000 volts. Large amounts of energy are dissipated close to the tree base. An animal or human sheltering beneath a tree would be seriously impacted.

Figure 75 gives the estimated voltage passing between two ground contacts at some distance (in feet) along a radial line from a tree lightning strike (30,000 amps) and separated by one foot (1 ft.) for different soil resistance values (in ohms). Soil resistance values vary with physical and chemical features of soil including organic matter content, soil texture, and water content. The greater soil resistance, the farther from a tree large ground voltages can be measured. For example, 10 feet away from a tree lightning strike with soil resistance of 200ohm, ground contacts would have a 87,000 volt difference, while with a 25ohm soil resistance the difference would be 10,000 volts.

Tree Impacts

Voltage moving through soil as the energy of a lightning strike is dissipated can be great, especially close to the tree and where soil resistance values are large. Tree interactions with dissipation of this energy occur due to root grafting, fine absorbing root distribution, and root contact points with other materials in the soil. Tree roots can be badly damaged close to a strike.

closest radial distance from tree (feet)	approximate voltage across ground contacts separated by 1 ft. radially (volts)	closest radial distance from tree (feet)	approximate voltage across ground contacts separated by 1 ft. radially (volts)
1 ft.	89,000 volts	70	1,000
2	46,000	80	1,000
3	32,000	90	1,000
4	25,000	100	1,000
5	20,000	150	800
6	17,000	200	500
7	15,000	250	475
8	13,000	300	395
9	12,000	400	300
10	10,000	500	240
20	5,000	600	200
30	3,000	700	170
40	2,000	800	150
50	2,000	900	132
60	1,000	1,000	120

Figure 73: Estimated voltage (step voltage) passing between two ground contacts separated along a radial line by one foot (1 ft.) at some distance (in feet) from a tree struck by lightning (30,000amps lightning strike & 25ohm soil resistance).

closest radial distance from tree stem (feet)	radial distance of separation between ground contacts 0.5 ft.	1.0 ft.	3.0 ft.	5.0 ft.
1 ft	66 kV	89	111	116
2	40	46	54	57
3	30	32	36	37
4	23	25	27	28
5	19	20	22	22
6	17	17	18	18
7	14	15	15	16
8	13	13	13	14
9	11	12	12	12
10	10	10	11	11

Figure 74: Estimated voltage (step voltage) passing between two ground contacts separated along a radial line by various distances (in feet) at some distance (in feet) from a tree stem struck by lightning. (30,000amp lightning strike & 25ohm soil resistance).

closest radial distance from tree stem (feet)	soil electrical resistance measures (ohms)							
	25	50	100	150	200	250	300	400
1 ft.	89kV	179	358	537	716	895	1074	1432
2	46	92	185	278	371	464	557	742
3	32	64	129	193	258	323	387	517
4	25	50	100	150	200	250	300	401
5	20	41	82	123	164	205	246	328
6	17	34	69	104	139	174	209	279
7	15	30	60	91	121	151	182	242
8	13	26	53	80	107	134	161	215
9	12	24	48	72	96	120	144	193
10	10	21	43	65	87	109	131	175
20	5	11	22	34	45	56	68	91
30	3	7	15	23	30	38	46	61
40	2	5	11	17	23	29	34	46
50	2	4	9	14	18	23	28	37

Figure 75: Estimated voltage (step voltage in kilovolts (kV)) passing between two ground contacts at some distance (in feet) along a radial line from a tree lightning strike (30,000amps) and separated by one foot (1 ft.) across various soil resistance measures (ohms).

Summarizing Lightning

Lightning strikes to trees generate heat and pressure from its arc. The pressure of this strong shock wave is applied perpendicular to tissues in a tree stem and can be greater than 40 atmospheres of pressure over distances of less than 1/5 inch. Figure 76. The rapid air expansion quickly slows and generates an acoustic wave heard as thunder within about 2 inches. Figure 77. (Few 1995; Hill 1977; MacGorman & Rust 1998). Other direct impacts of lightning on a tree include heat generation from resistive heating in tissues and associated steam generated expansion. The strong shockwave generated by the lightning core represents about ten times more energy released than tissue heating and steam expansion.

Lightning messes-up trees badly!

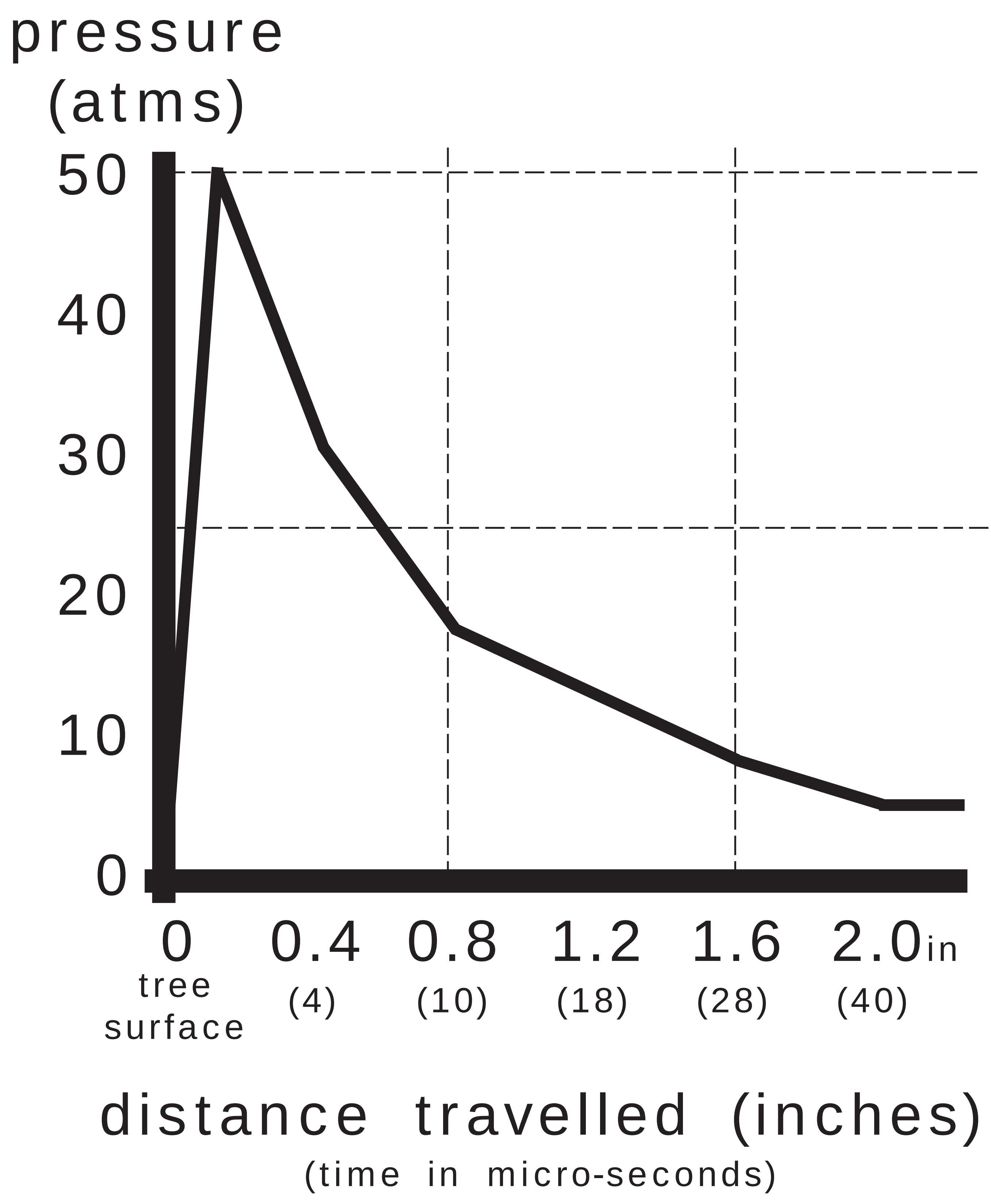


Figure 76: Shock wave pressures,decaying into acoustic wave over time and space, spreading away from lightning core. (derived from Few 1995; MacGorman. & Rust 1998)

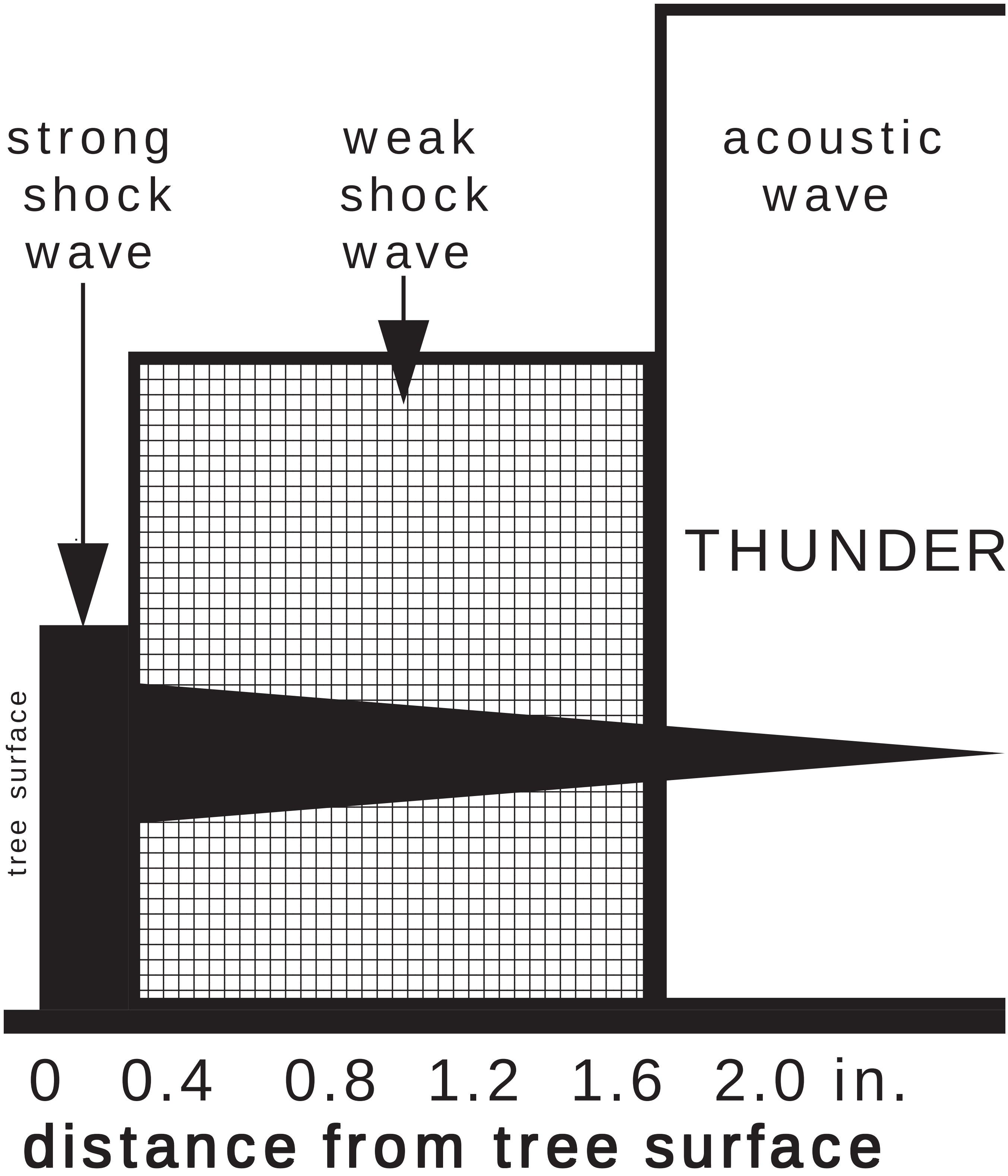


Figure 77: Pressure wave expanding from lightning core.
(Few, 1995)

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