Electrical structure of lightning-producing clouds

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- Thunderclouds: basic facts -> cumulonimbus
- Theory: Tripole model of charge structure and lightnings in it
- Remote measurements
- *In situ* observation

Lightning-producing systems

Clouds of smoke: over forest fires, volcanos, sandstorms…

"Clean" clouds

↓

Cumulonimbus

Lightning-producing cloud

Sun energy ->

- Wind (horizontal and vertical)
- Outflow of condensate (rain snow, ice crystals)
- Electrical discharges (lightnings, sprites, elves, jets, jets…)

10 m/s

3-50 km

10-30 km/h

Hydrometeors:

- Precipitation particles

(with fall speeds >= 0.3 m/s)

- Cloud particles

Development of a thundercloud

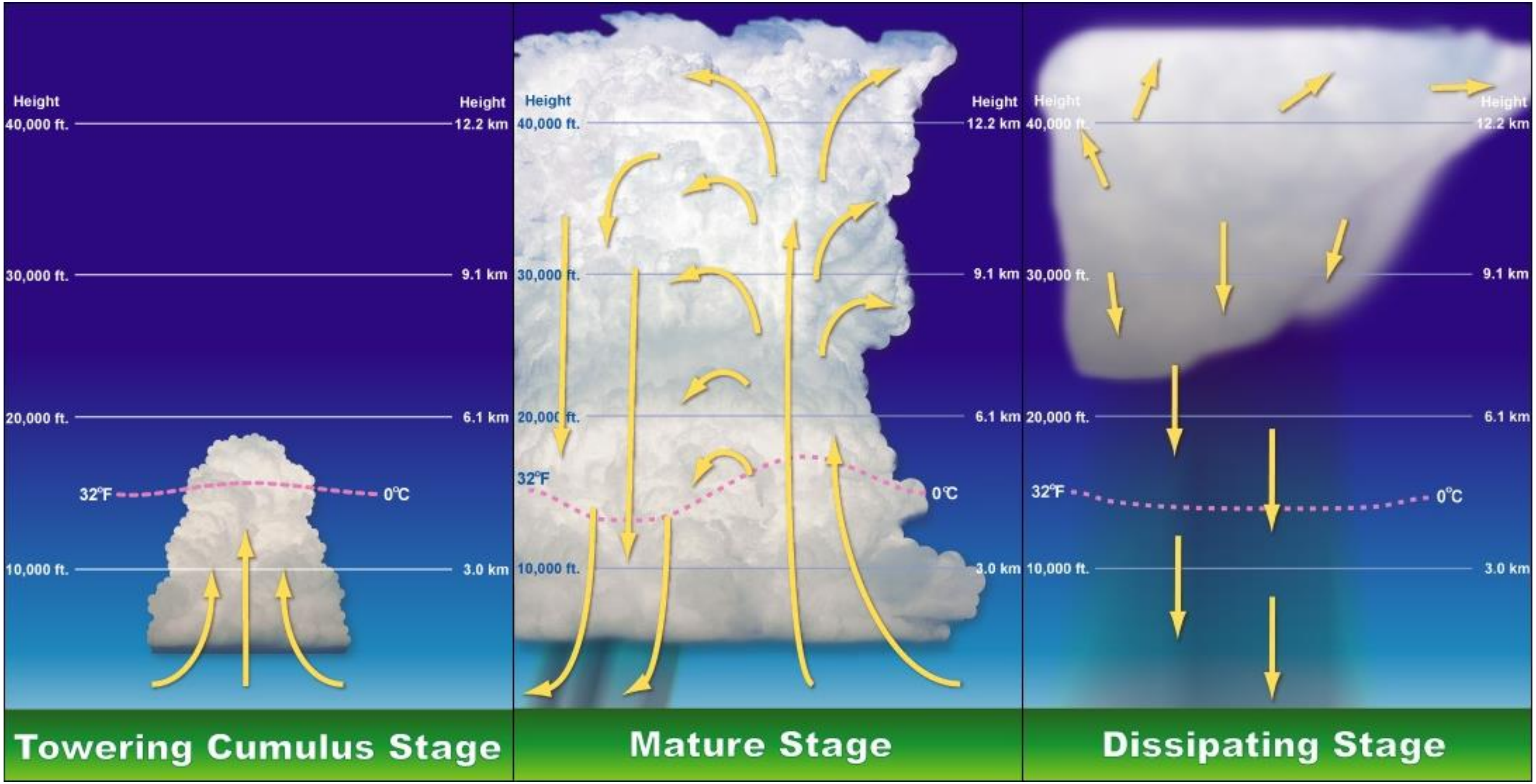
Water vapour →  → 

Adiabatic expansion, cooling

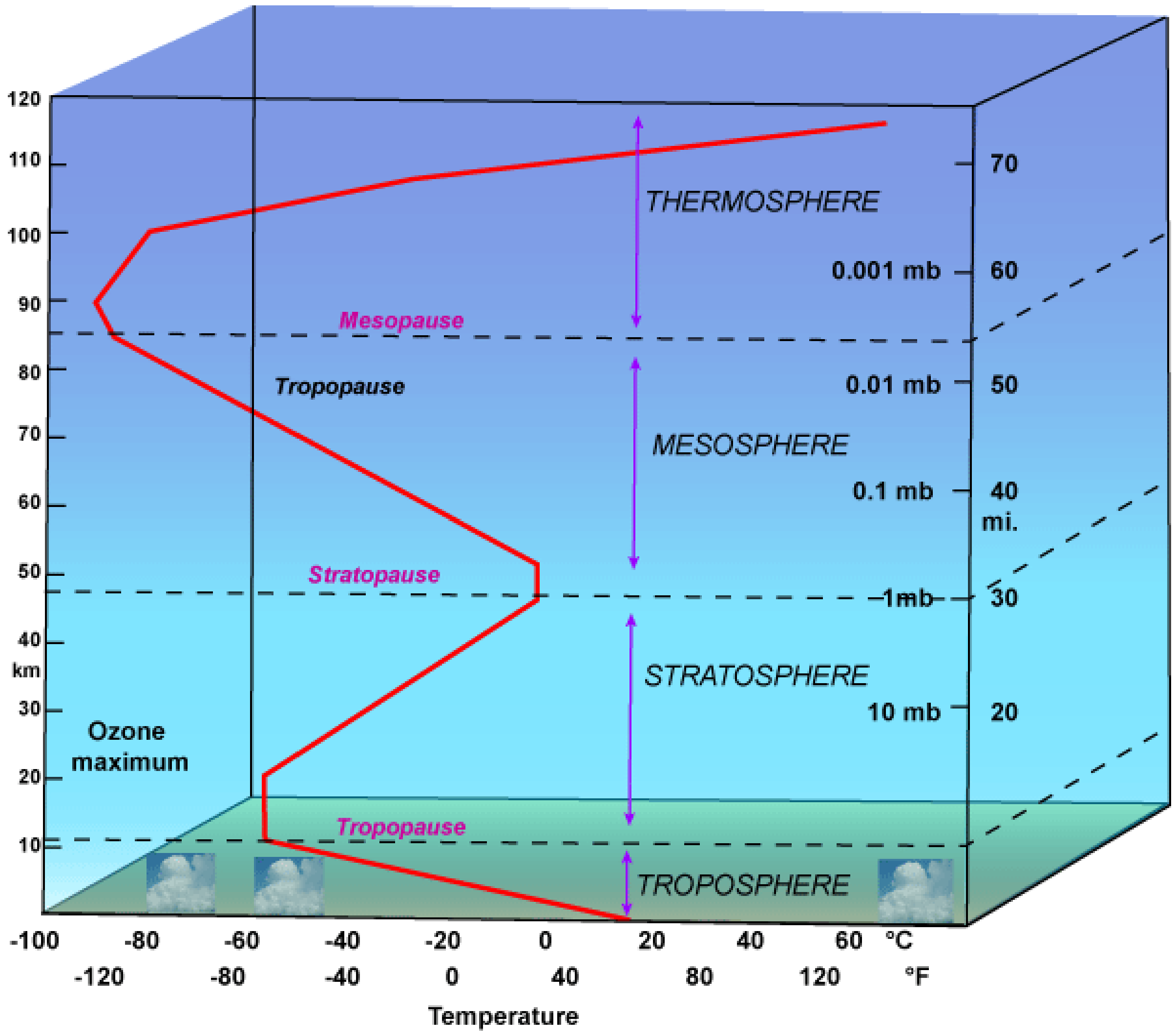
Cumulus – fair-weather cloud

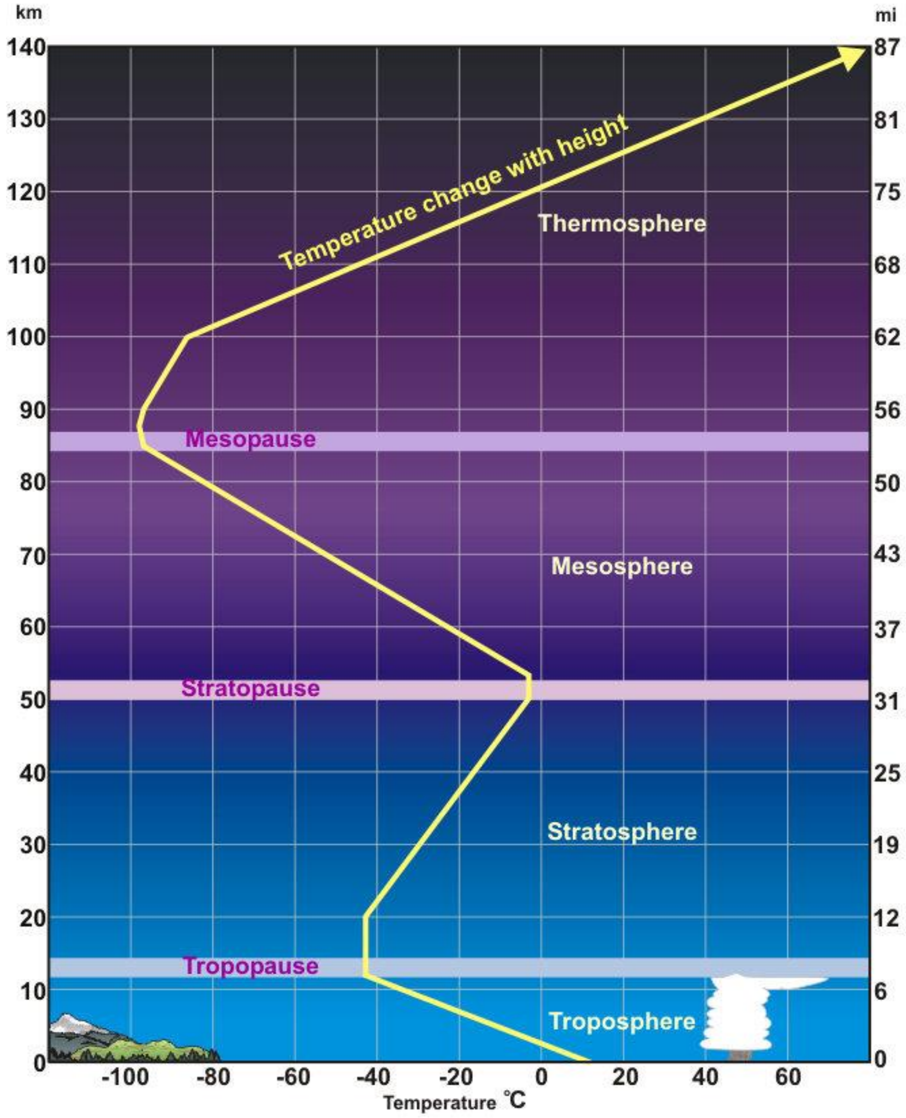
Base of the cloud – at the height of the condensation level

Evolution of thundercloud

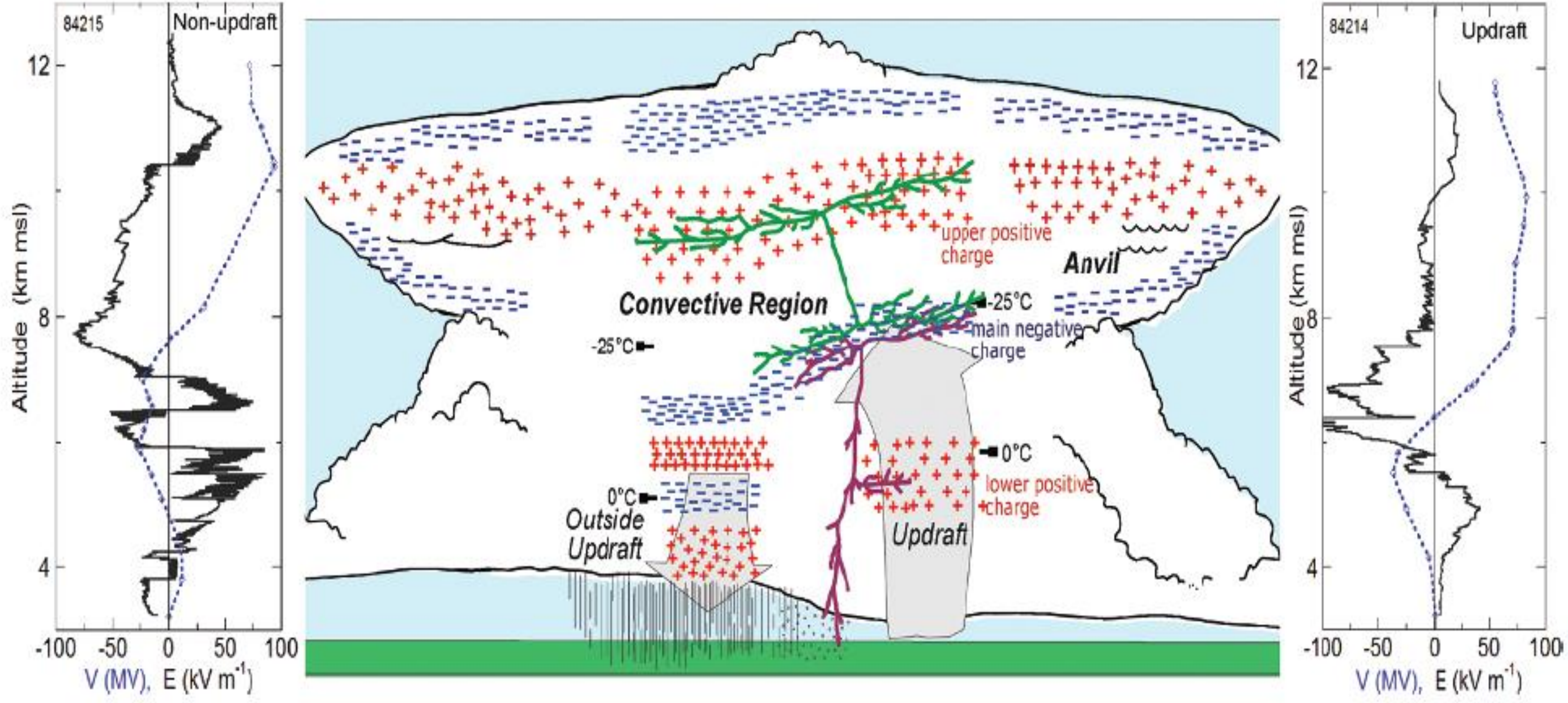


Temperature profile of the atmosphere





Electric cloud structure: remote and in situ observations evidence

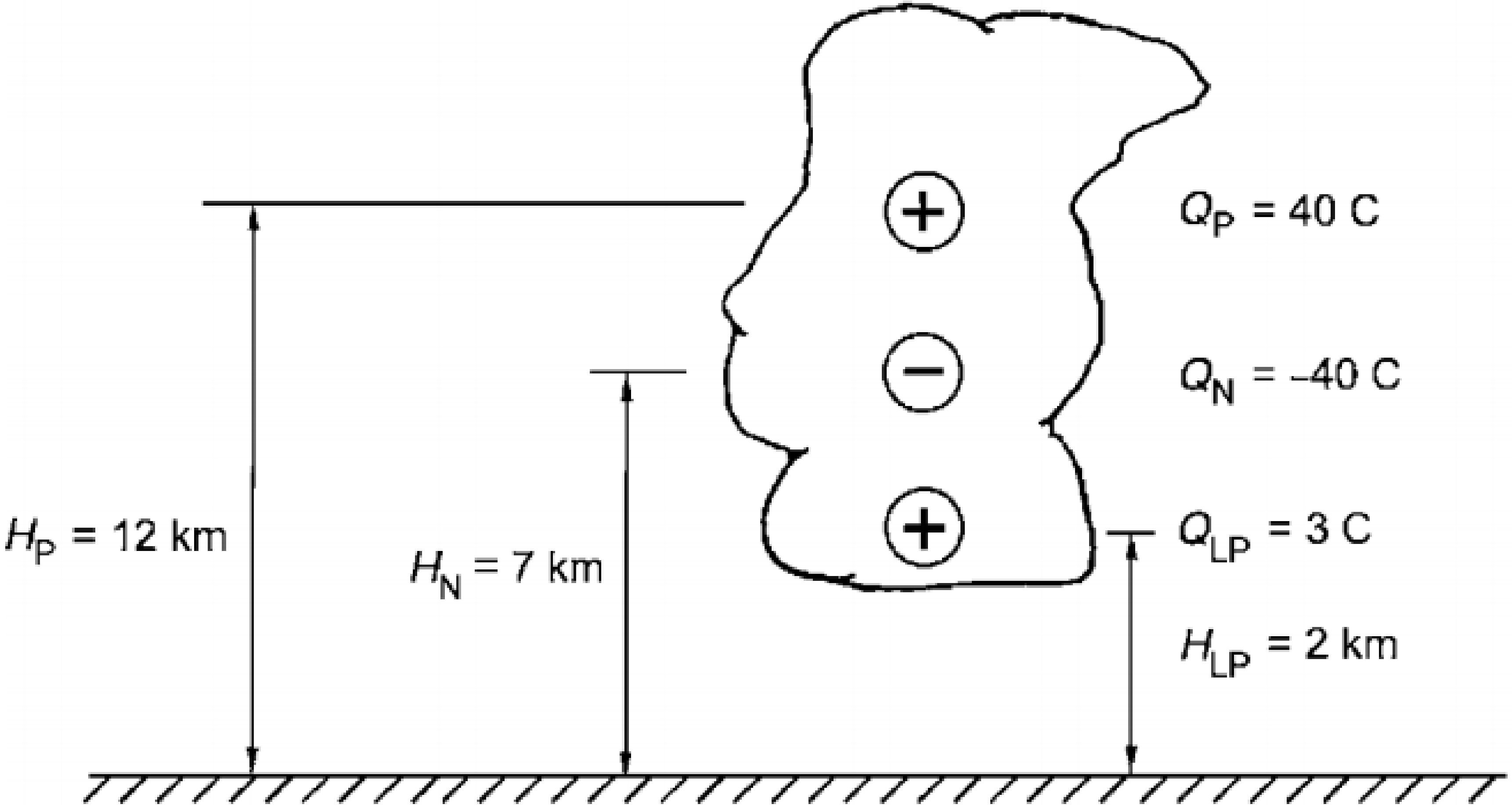


[Stolzenburg and Marshall, 2009]

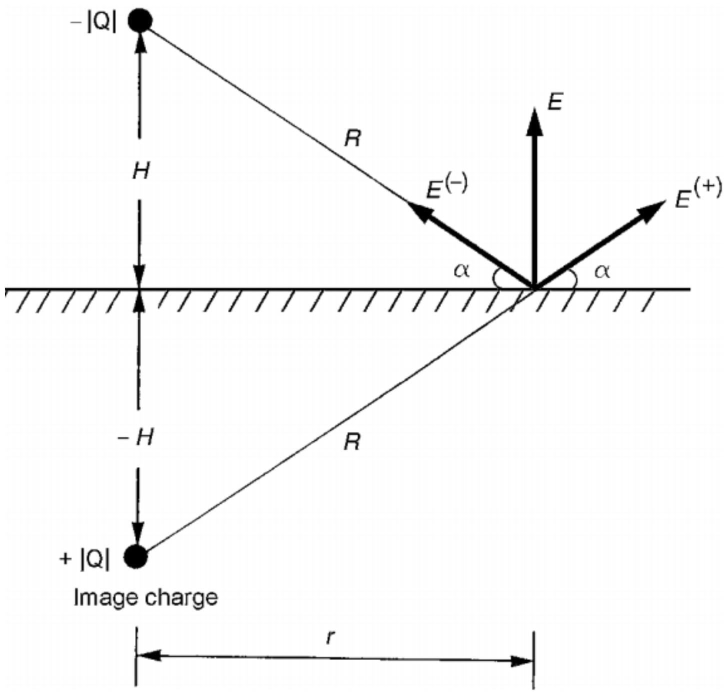
Electric cloud structure: remote and in situ observations evidence

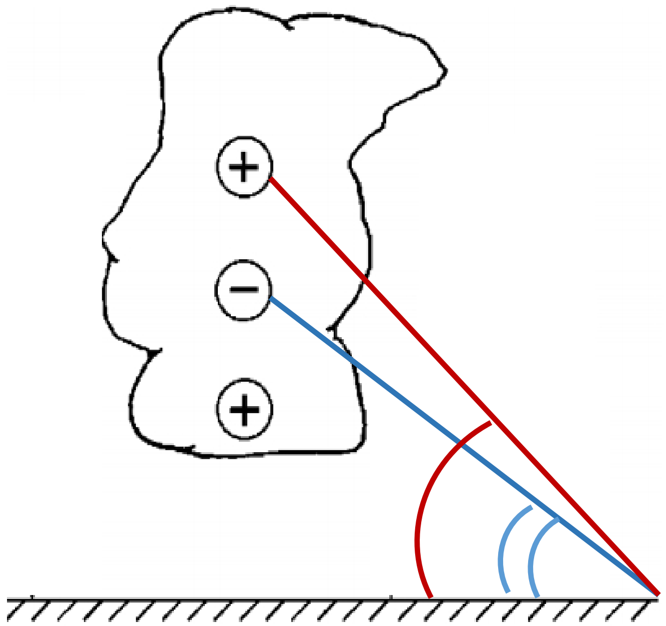
Fig. 3.1. An isolated thundercloud in central New Mexico, with a rudimentary indication of how electric charge is thought to be distributed inside and around the thundercloud, as inferred from the remote and *in situ* observations discussed in subsections 3.2.2 and 3.2.3, respectively. Adapted from Krehbiel (1986).

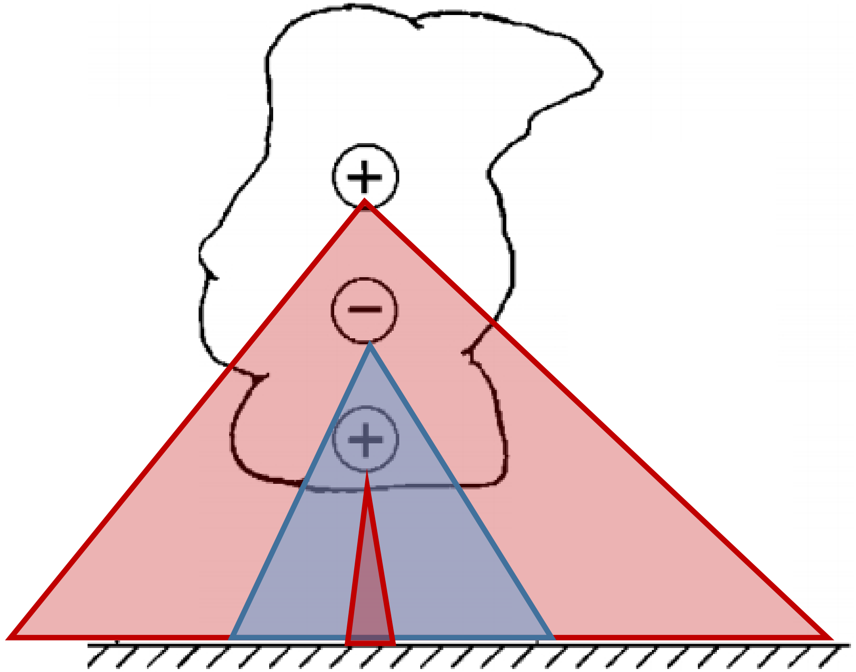
Cloud electric structure: Tripole model



Ground-level field of a single charge and it’s “image”



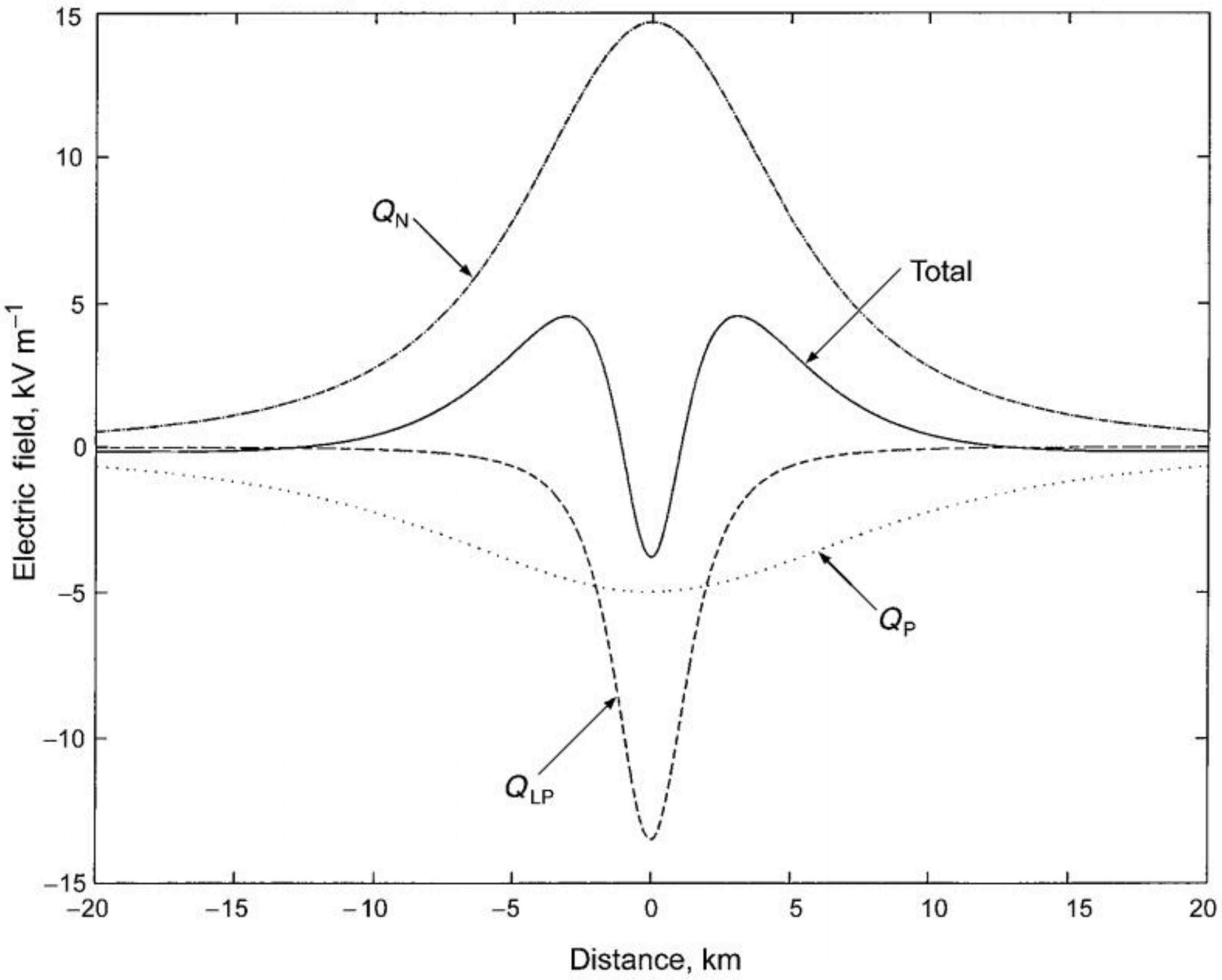




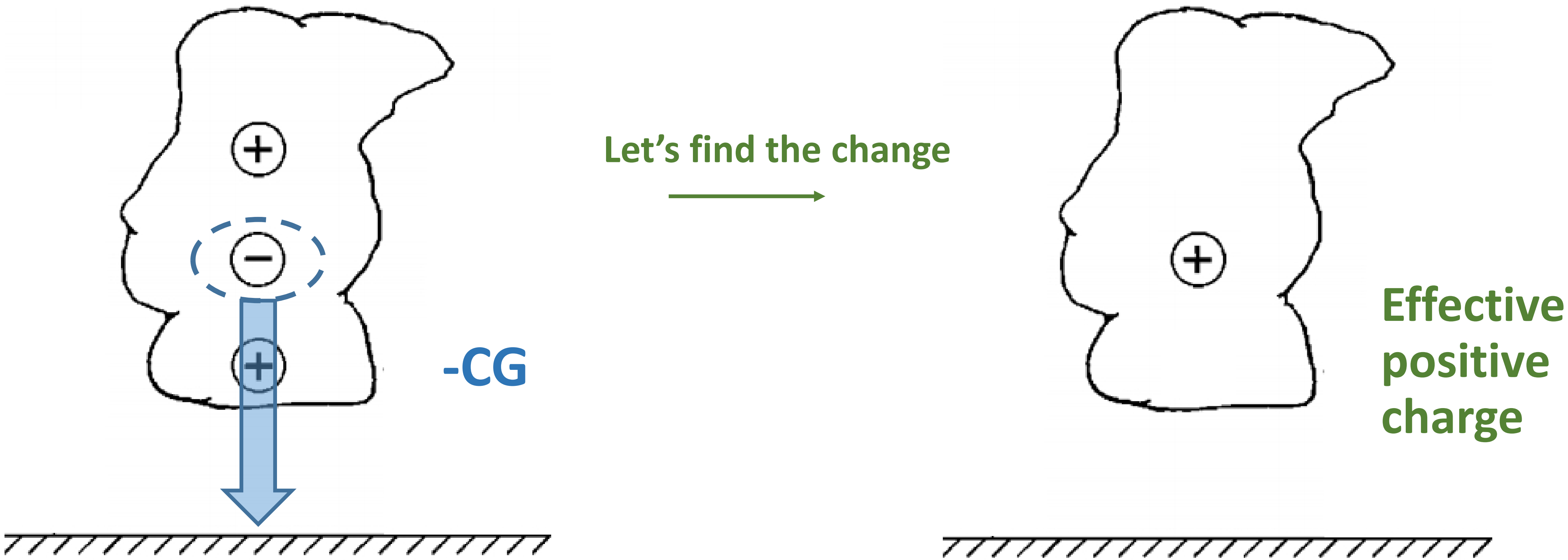
$$|\mathbf{E}| = k\frac{\sin\alpha}{R^2}$$

where $k = |Q|/(2\pi\varepsilon_0)$ and $R^2 = (H^2 + r^2)$

Tripole charge structure: field at the surface



Cloud-to-ground discharge -> ground-level field change



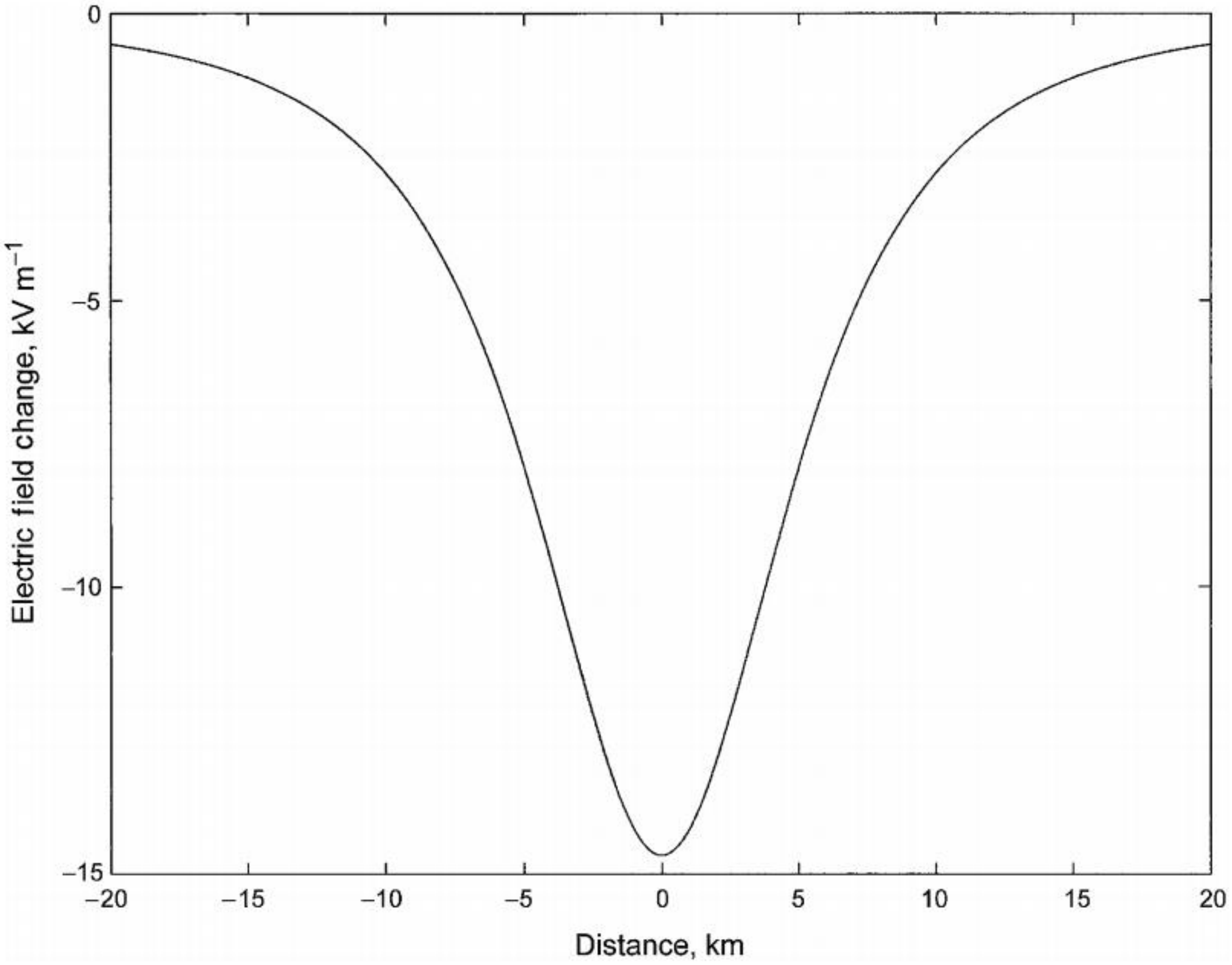
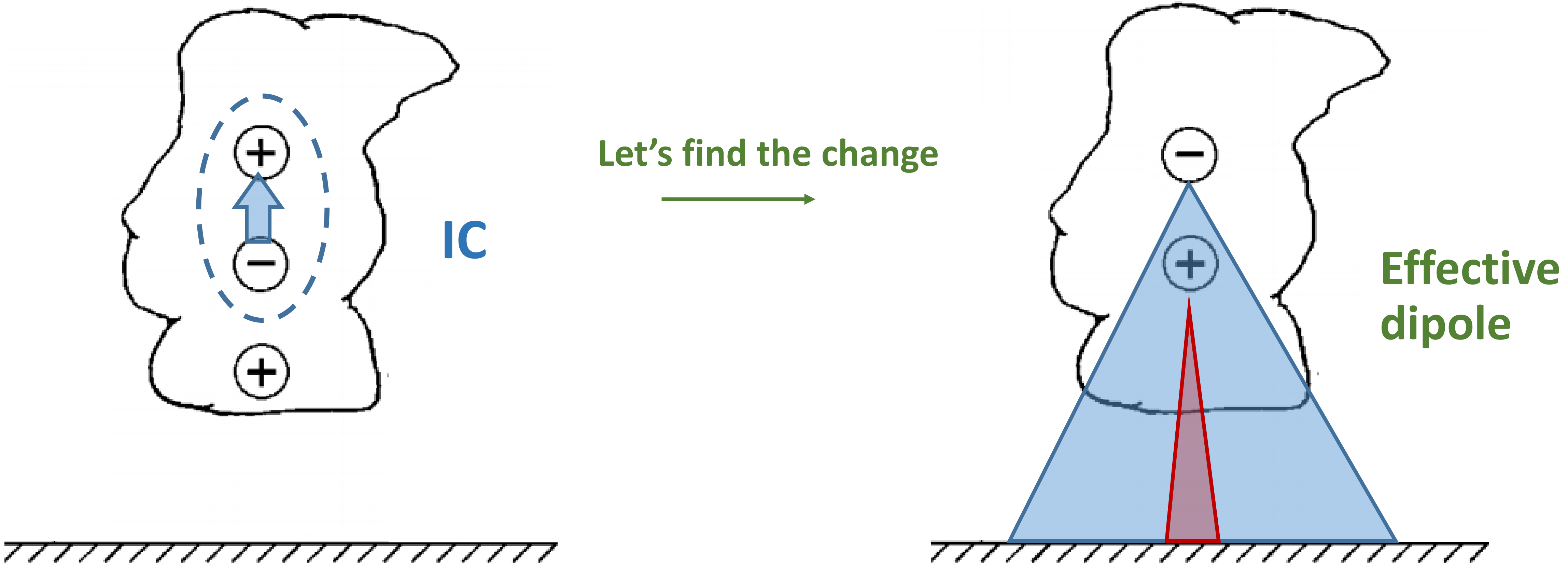


Fig. 3.2d. Electric field change at ground, due to the total removal of the negative charge of the vertical tripole shown in Fig. 3.2a via a cloud-to-ground discharge, as a function of distance from the axis of the tripole. Note that the electric field change at all distances is negative.

Intracloud discharge -> ground-level field polarity reversal



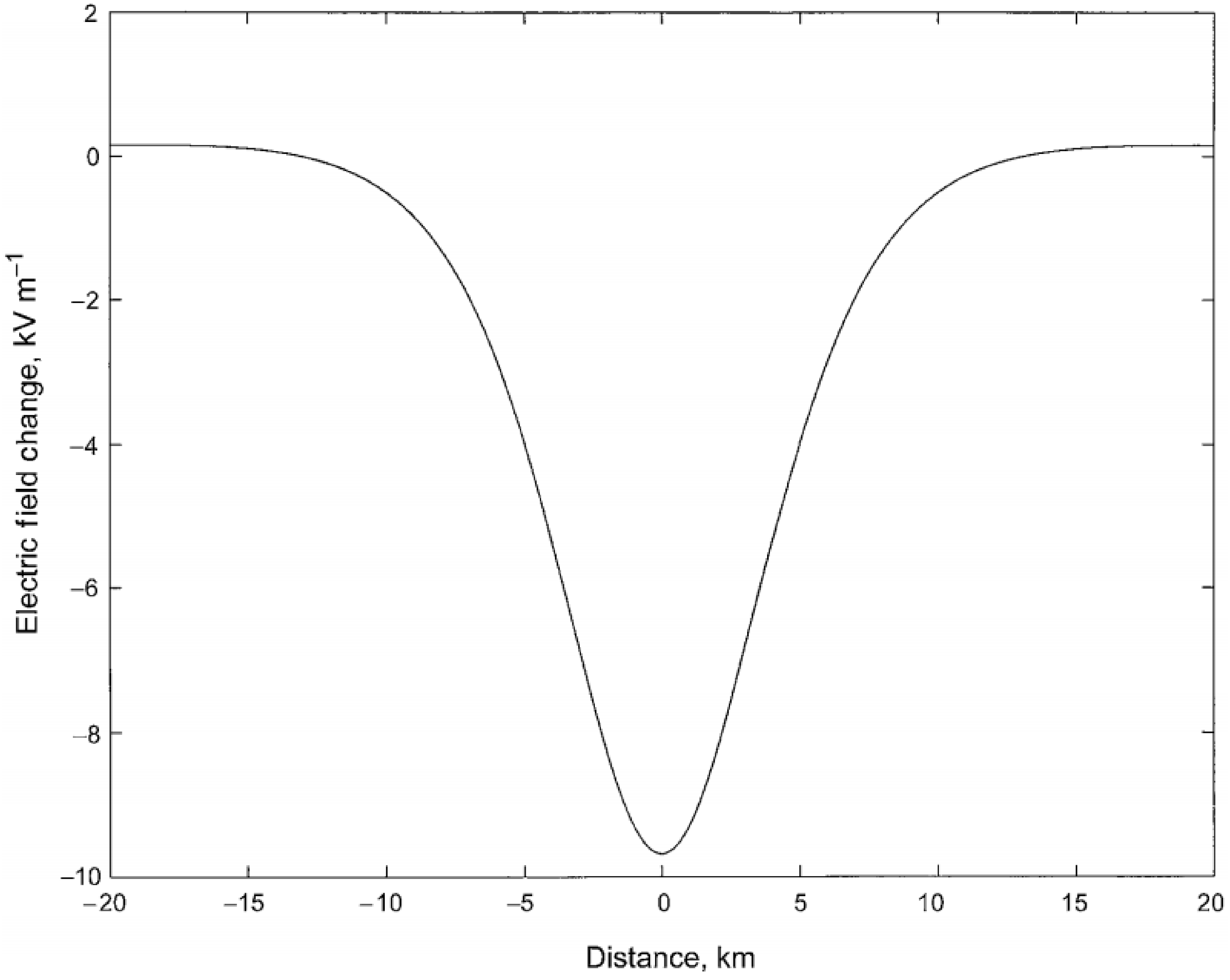
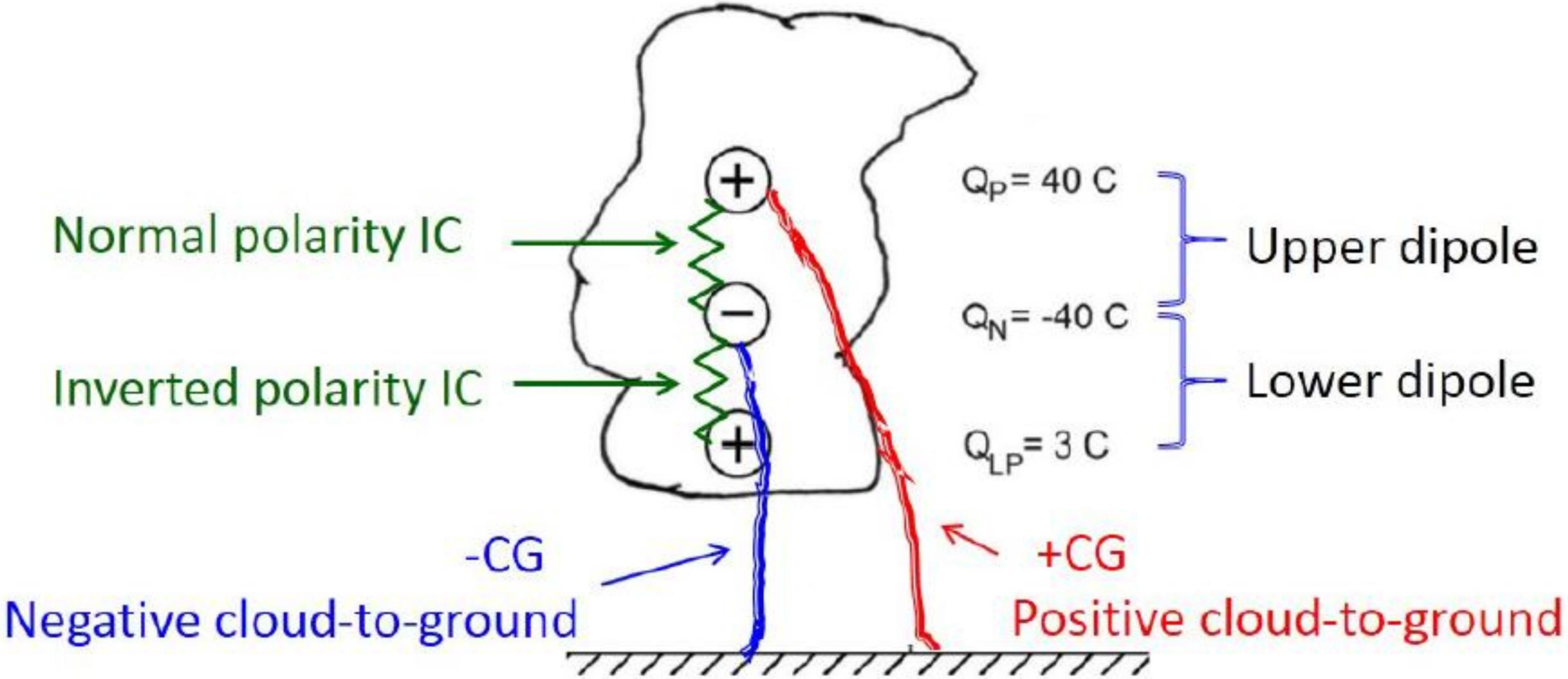


Fig. 3.2e. Same as Fig. 3.2d, but due to the total removal of the negative and upper positive charges via a cloud discharge. Note that the electric field change at close distances is negative, but at far distances it is positive.

Discharges -> ground-level field sign reversal



Chilingarian et.al., 2017, “Types of lightning discharges that abruptly terminate enhanced fluxes of energetic radiation and particles observed at ground level”

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Inferences from remote measurements

Remote measurements: at ground level or above cloud tops

- Slowly varying field – movement of cloud charges – about 10 minutes
- Rapid field changes – lightning discharges – about 1 minute

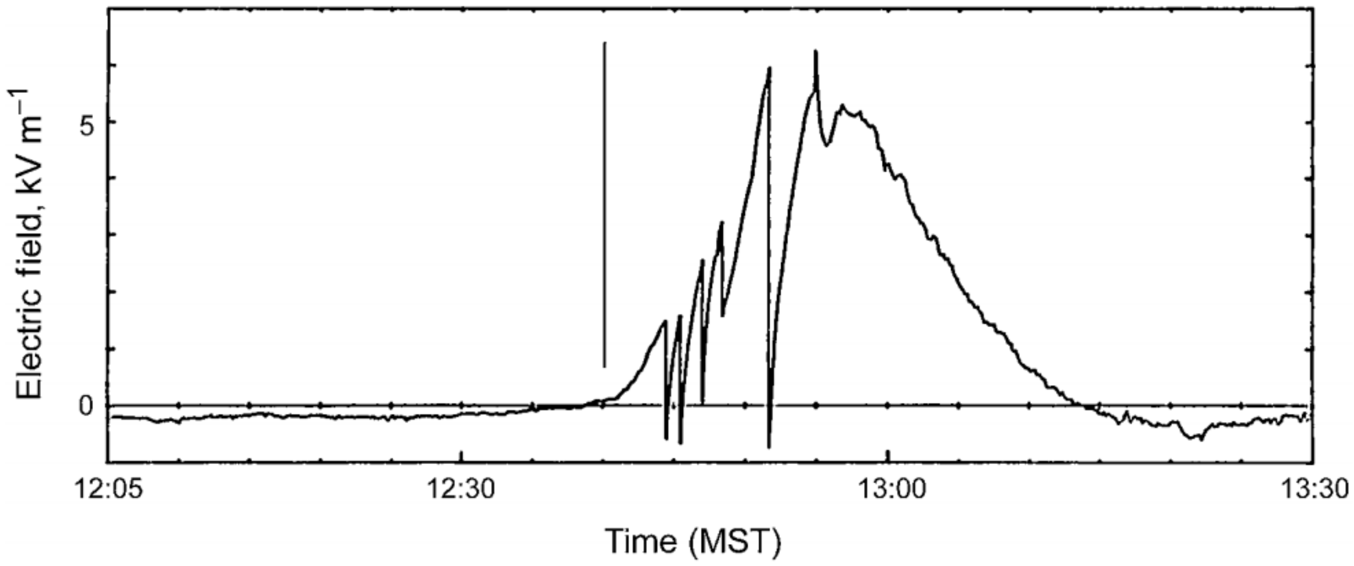


Fig. 3.3. Electric field at the ground about 5 km from a small storm near Langmuir Laboratory, New Mexico, on 3 August 1984. An upward-directed electric field is defined as positive (according to the physics sign convention; see subsection 1.4.2). The large pulses superimposed on the rising portion of the overall electric field waveform are due to lightning. Adapted from Krehbiel (1986).

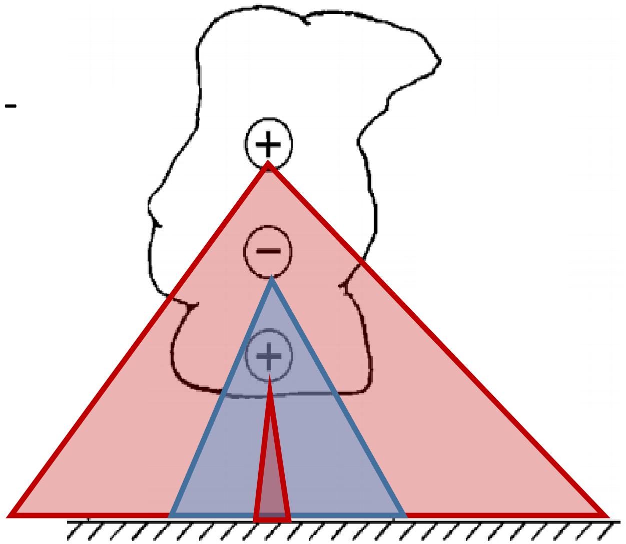
Typical values of ground-level electric field:

- Fair weather: 100 V/m, directed downwards
- Beneath an active thundercloud: 1-10 kV/m

Inferences from remote measurements

Wilson (1916, 1920, 1929):

- Systematic variation in the polarity of electric field on the both time scales
- At close ranges field tend to be upward-directed, at far ranges – downward-directed -> "a positive dipole"
- Field changes by lightnings are more often directed downwards nearby, than far away -> probably, IC flashes are more numerous than CG and predominantly are "normal polarity"; and –CG are more common than +CG



Jacobson and Krider (1976), the KSC electric field-mill network:

- A total flash charge of -10 to -40 C was lowered to ground from a height of 6 to 9.5 km above sea level, a height where the clear-air temperature was between -10 and -34 ◦C

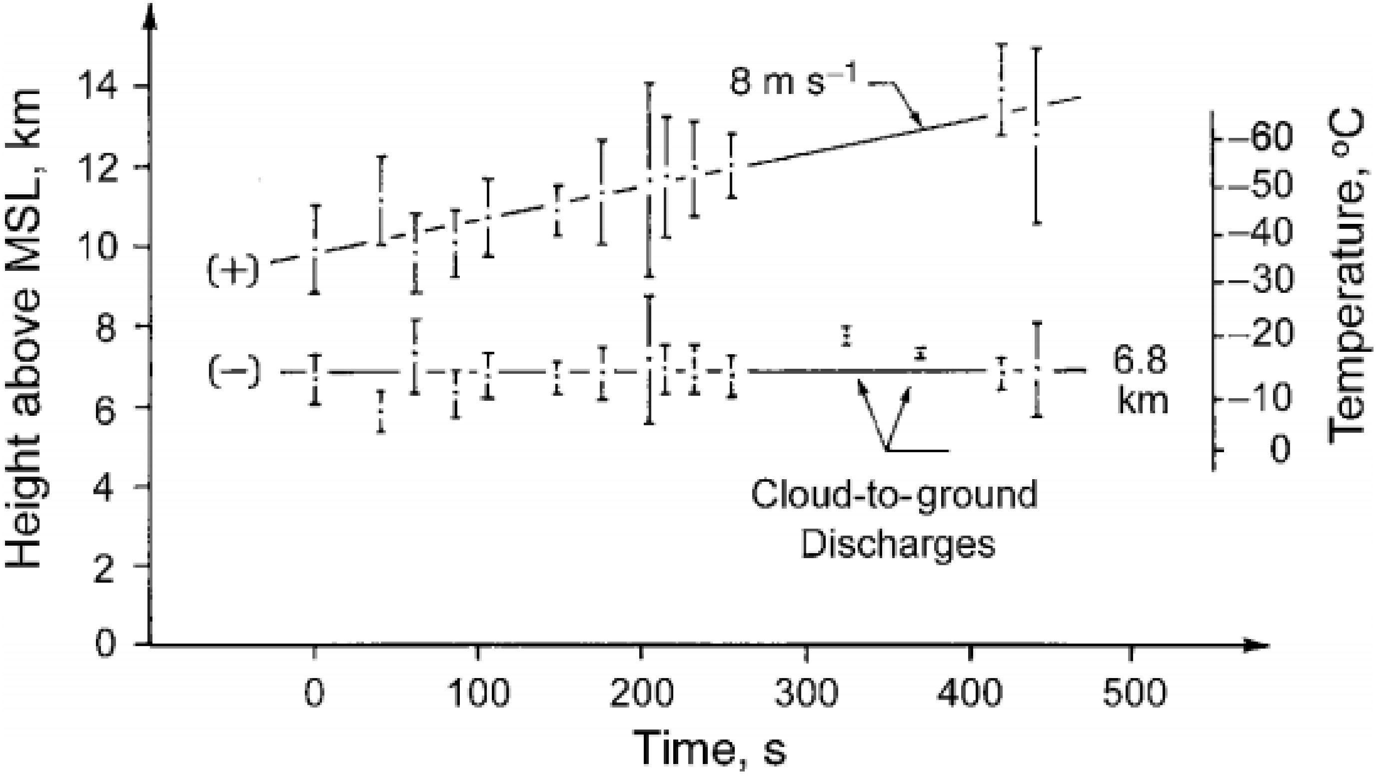
Maier and Krider (1986), the KSC electric field mill network:

- The altitude from which the negative
  flash charge is lowered varies very little from flash to flash
  throughout a given day, but it does vary from day to day

Inferences from measurements: temperature values

Krehbiel (1986):

- The negative charge center involved in lightning flashes remains at an approximately constant altitude as a storm grows
- As the storm grew vertically, the positive (upper) charges involved in cloud flashes tended to be found at progressively higher altitudes, increasing in time from 10 km (-30 ◦C) to 14 km (-60 ◦C) during the 8 min period of observation.
- The negative (lower) charges involved in cloud flashes and the negative charges neutralized by
  ground flashes remained at about 7 km altitude (-15 ◦C)



Inferences from remote measurements

Krehbiel *et al*. (1979), an eight-station electric-field-change measuring system in New Mexico :

- The magnitudes of the charges lowered to
  ground by individual strokes and by continuing currents in four multiple-stroke flashes are determined
- The charges were displaced primarily horizontally in a relatively narrow range of heights from 4.5 to 6 km (one exception, 3.6 km) above ground

Proctor (1991, a VHF–UHF TOA lightning locating system:

- The distribution of origin heights flashes has two peaks at 5.3 and 9.2 km amsl (1 ◦C to -9 ◦C and -25 ◦C to -35 ◦C)

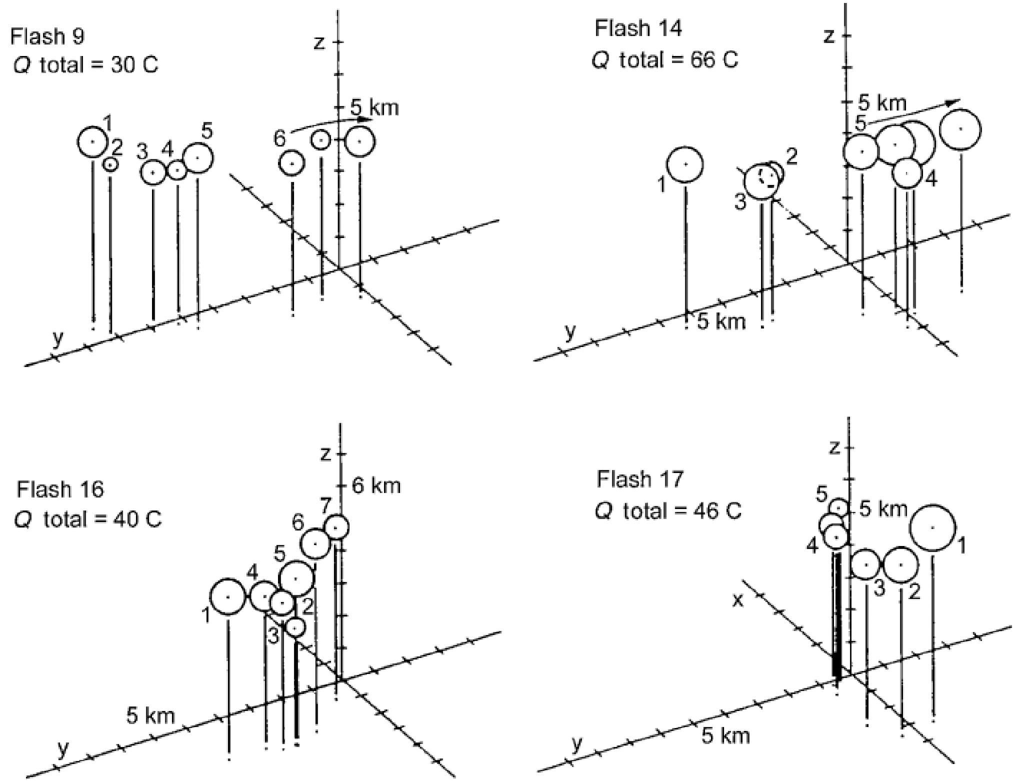


Fig. 3.5. Charge source locations for strokes and continuing currents in four multiple-stroke flashes in New Mexico. All strokes are numbered sequentially. In the case of strokes followed by continuing current, two or more locations appear under one number (this applies to the following: flash 9, event 6; flash 14, event 5; flash 17, event 4). In flashes 9 and 17, the continuing-current charges are incremental while in flash 14 they are cumulative from the beginning of stroke 5, except for the last charge which is incremental. The charge magnitude is represented by the size of the sphere surrounding the charge location point, the radii of the spheres being determined assuming a charge density of 20 nC m^{-3}. The electric fields versus time at eight stations for flash 14 are given in Fig. 4.9. Adapted from Krehbiel *et al*. (1979).

Results of the remote measurements analysis:

- the negative charge involved in lightning flashes tends to have a relatively small vertical extent that is apparently related to the -10 to -25 ◦C temperature range, regardless of the stage of storm development, the location, and the season.
- The main positive charge involved in lightning flashes probably has a larger vertical extent and is located above the negative charge.
- An additional, smaller, positive charge can be formed below the negative charge.

Difficulties of the model for remote measurements:

- The overall charge of each polarity is not uniformly distributed in a single spherical area
- Precipitation particles carrying charge of either polarity at nearly all altitudes.
- Besides the charged regions in the cloud interior - “screening charge layers”.
- The main negative charge causes corona from various pointed objects on the ground
- The interpretation of remote measurements of the electric fields produced by cloud charges is not unique: many different charge distributions can produce similar variations of the remote electric field as a function of distance from the cloud.

Inferences from *in situ* measurements

In situ measurements: free balloons carrying corona probes, free balloons carrying electric field meters, aircraft, rockets, parachuted electric field mills

According to Gauss's law in point form,
$\rho v = \varepsilon 0$ (d*Ez*/dz).

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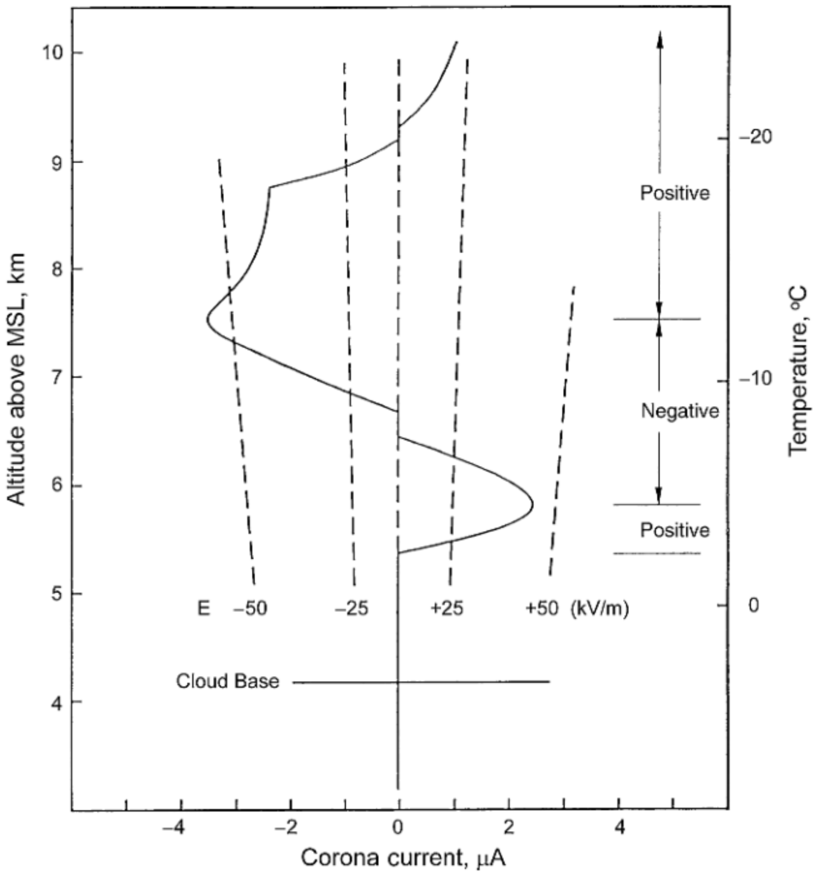


Fig. 3.9. Balloon measurements of corona current and the inferred vertical electric field *E* versus altitude and air temperature inside a small storm in New Mexico on 16 August 1981, which produced no lightning. The sign convention is that a positive current is induced by an upward-directed electric field, which is defined as positive. The charge regions are labeled positive or negative on the right. The profile is indicative of the "classical" tripole. The total time to acquire the record above cloud base (at roughly 4 km) was about 11 min. Adapted from Byrne *et al*. (1983).

Inferences from *in situ* measurements

Simpson and Scrase (1937), Simpson and Robinson (1941); ascending balloons:

- Cloud charge structure was composed of three vertically stacked charges (a tripole): a lower positive charge of +4 C at temperatures warmer than 0 ◦C, a main negative charge of -20 C between 0 ◦C and -10 ◦C, and a main positive charge of +24 C at temperatures colder than -10 ◦C.

Marshall and Rust (1991):

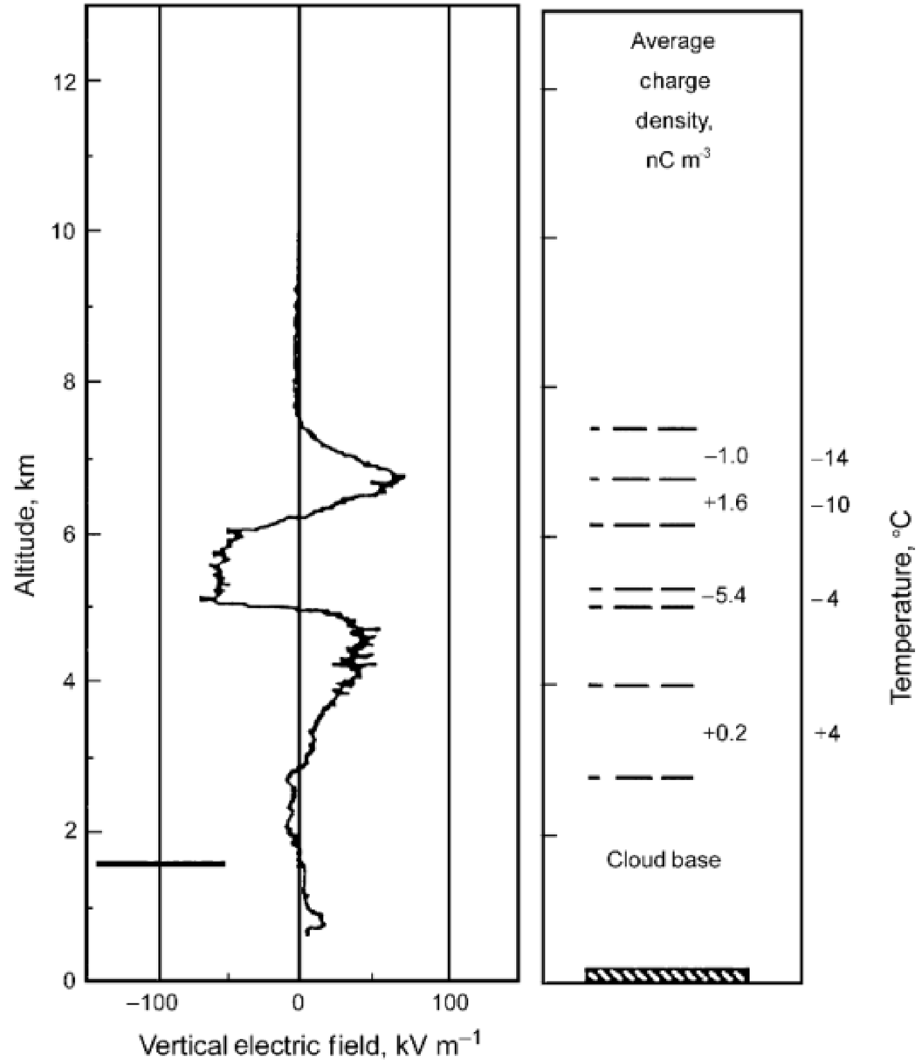
- 4 to 10 charge layers, vertical extent: from 130 m to 2.1 km.

Marshall and Stolzenburg (2001), from 13 balloon soundings:

- Estimated cloud top voltages ranging from -23 to +79 MV relative to the Earth. Within clouds, the voltage values ranged from -102 to +94 MV in 15 soundings.

Stolzenburg *et al*. (1998a, b, c), nearly 50 balloon electric field soundings:

- Tripole structure – in strong updrafts; structure of about 6 layers – outside updrafts.



Results of *in situ* measurements analysis:

- Tripole model sometimes could be sufficient for the charge structure description
- There is a screening layer at the upper cloud boundary and there may be up to six extra charge regions, usually in the lower part of the cloud

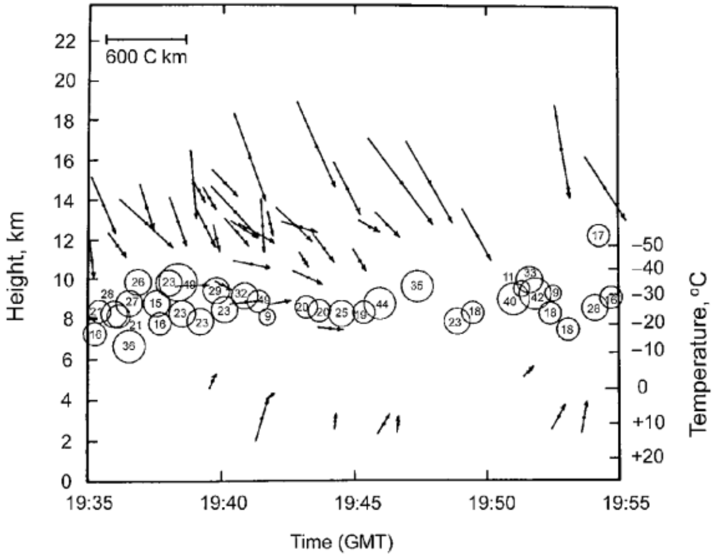
The difficulties of *in situ* measurements:

- The charge magnitude can be estimated only if assumptions regarding the size and shape of individual charge regions and the charge variation with time are made.
- The average volume charge density in the cloud is generally found by assuming that the charge is horizontally uniform and does not vary in time.
- The time required for a balloon to traverse a cloud, 30–45min,
is comparable to or exceeds the typical duration of the mature stage of a thunderstorm cell.

Inferences from measurements: temperature values

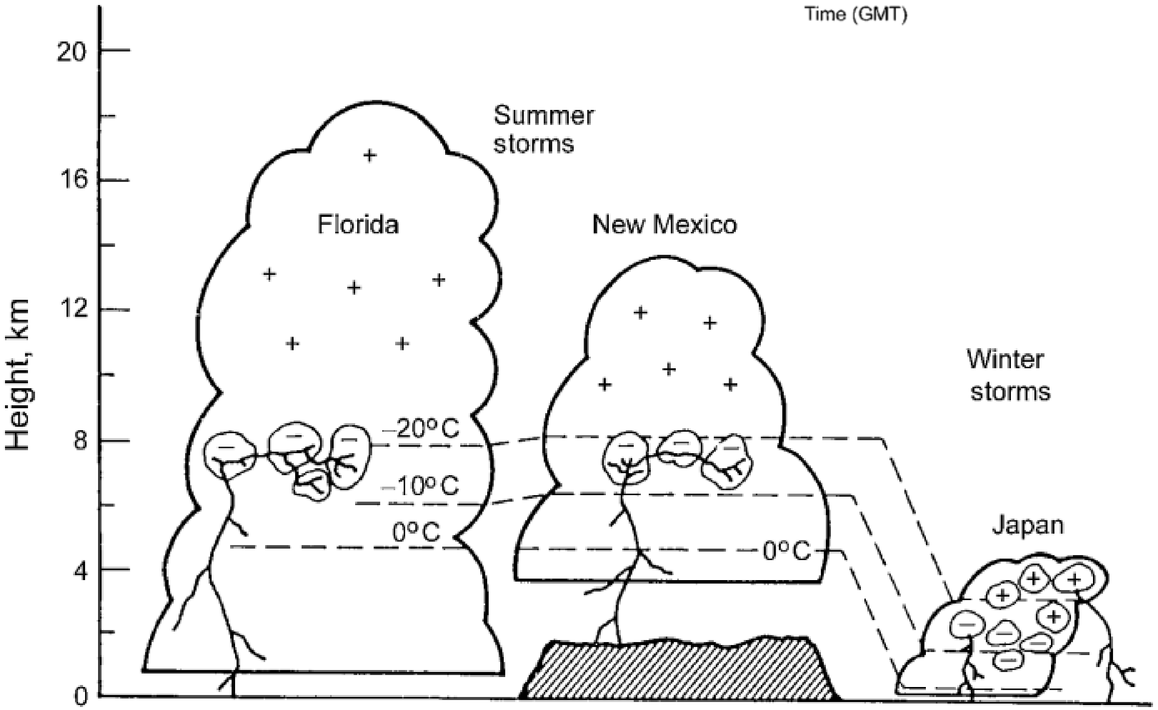
A combination of remote and *in situ* measurements:

- In very different environments negative charge is typically found in the same relatively narrow temperature range, roughly -10 to -25 ◦C, where the clouds contain both supercooled water and ice.

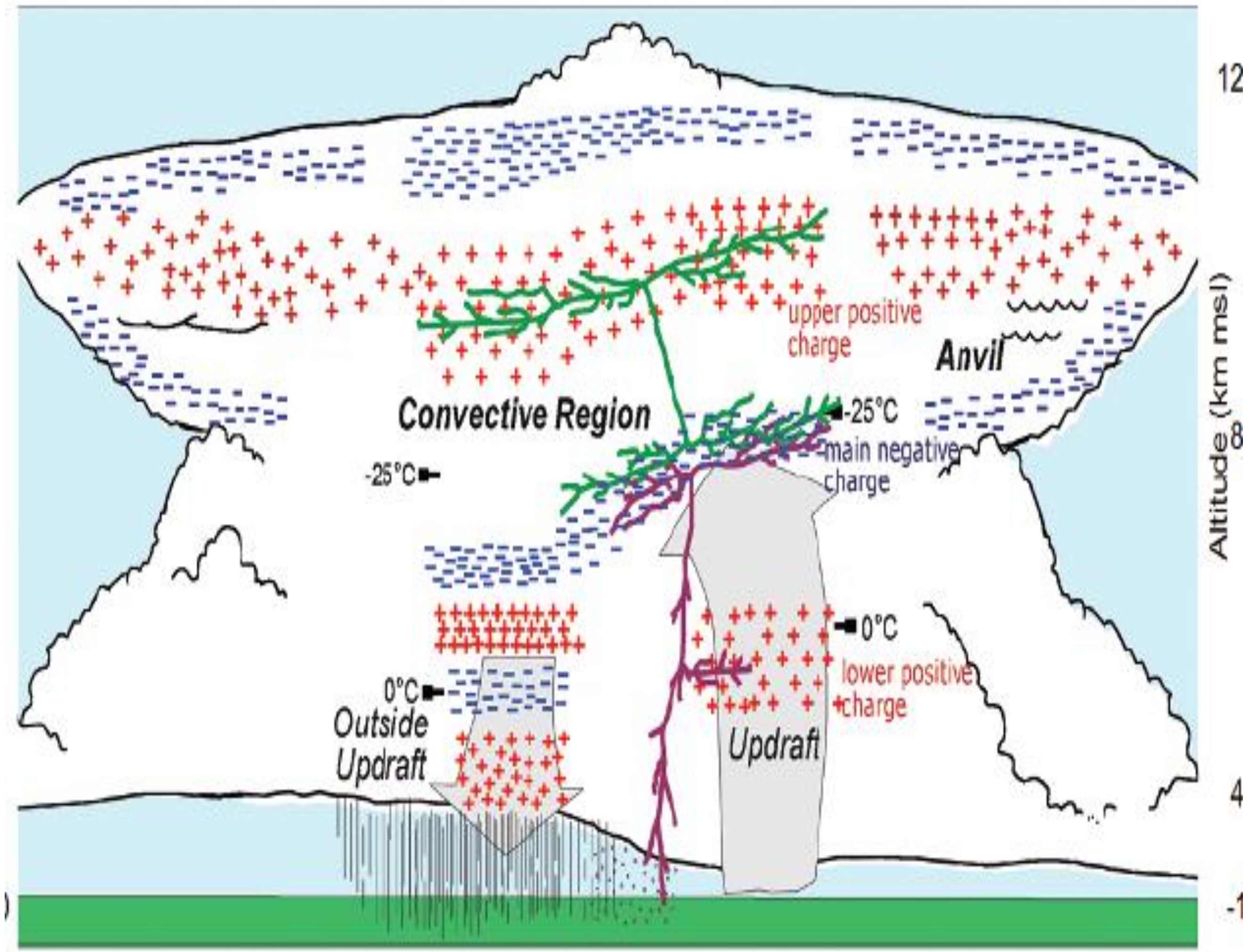


Stolzenburg *et al*. (1998a,b,c), from *in situ* balloon soundings:

- the average temperature of the center of the main negative charge region may depend on storm type: -16 ◦C in MCS convective region updrafts, -22 ◦C in supercell updrafts, and -7 ◦C in New Mexican mountain storm updrafts.



Thank you!



12
8
4
-1
Altitude (km msl)
upper positive
charge
Anvil
Convective Region
-25°C
main negative
charge
-25°C
0°C
lower positive
charge
0°C
Outside
Updraft
Updraft