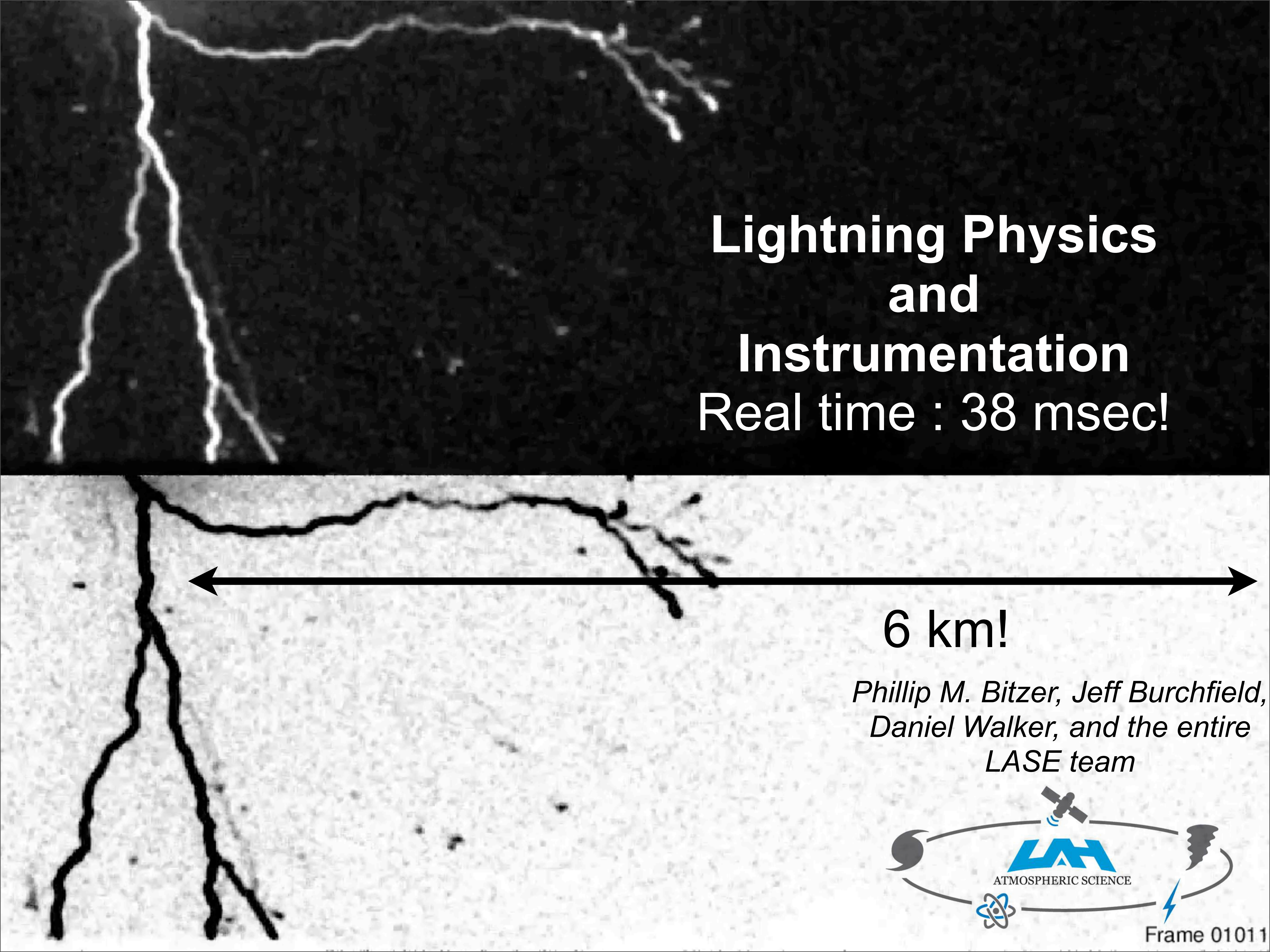


Lightning Physics and Instrumentation

Real time : 38 msec!

Phillip M. Bitzer, Jeff Burchfield, Daniel Walker, and the entire LASE team

ATMOSPHERIC SCIENCE

Lightning…it’s electrifying!

Cloud to ground lightning starts with a ***stepped leader***

It is a hot plasma and is self propagating

It has a typical speed of $2x10^5$ m/sec

Typical (linear) charge density is 2 C/km

The return stroke can reach temperatures >5x the surface of the sun (30000 K)

Typical peak current is 30 kA (early) and 15 kA (late)

Typical electron density of the channel is 10^{18} cm^{-3}

The current (and luminosity) wave propagates up the channel

As the stepped leader nears the ground, upward leaders are initiated

Once the connection is made, the large potential difference between cloud and ground is shorted

Typical connection height is ~100 m

Not just one leader....


3.3 km

50 milliseconds later....

As an aside, this stroke was located ~5km from the first...


1st leader

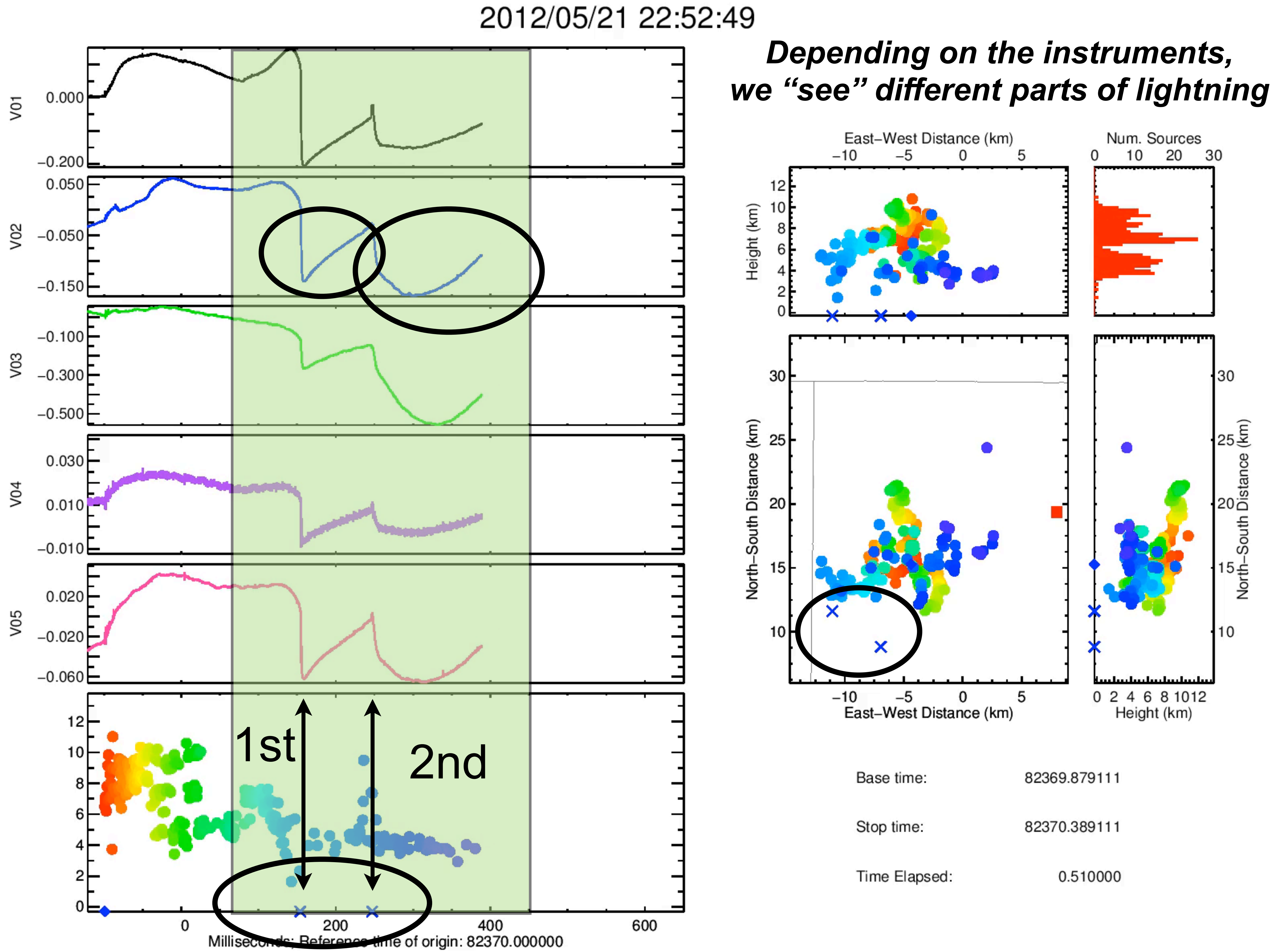
2nd leader


1st leader
2nd leader

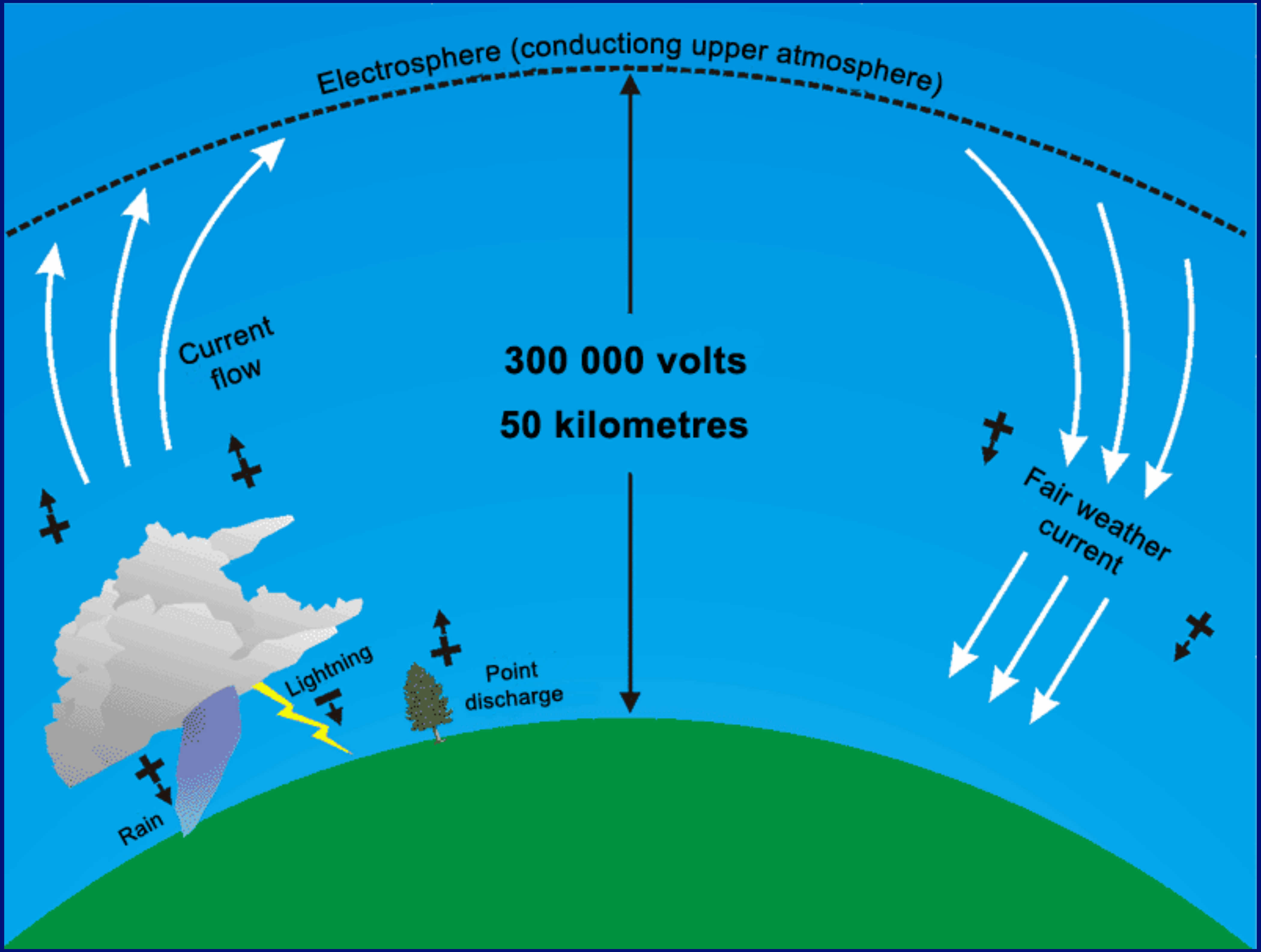
We call this a ***dart leader***

Same path!

Depending on the instruments, we "see" different parts of lightning

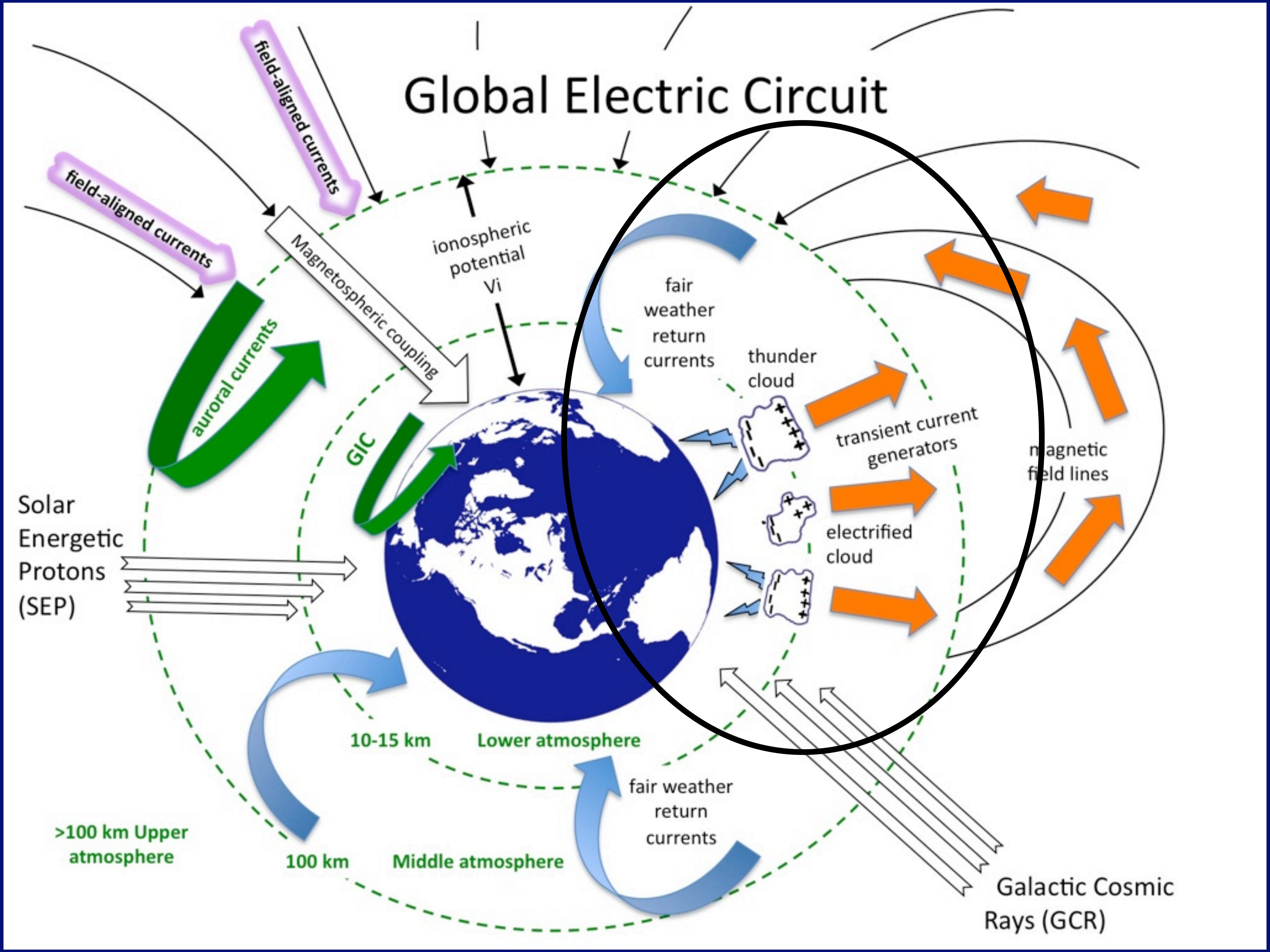


Even in “fair” weather, there is a current flowing in the atmosphere.....



We refer to this as the global electric circuit (DC)

*The **fair weather field** is about -100 V/m (at the ground)*



Global Electric Circuit
field-aligned currents
field-aligned currents
Magnetospheric coupling
ionospheric potential Vi
auroral currents
GIC
fair weather return currents
thunder cloud
transient current generators
electrified cloud
magnetic field lines
Solar Energetic Protons (SEP)
10-15 km
Lower atmosphere
fair weather return currents
>100 km Upper atmosphere
100 km
Middle atmosphere
Galactic Cosmic Rays (GCR)

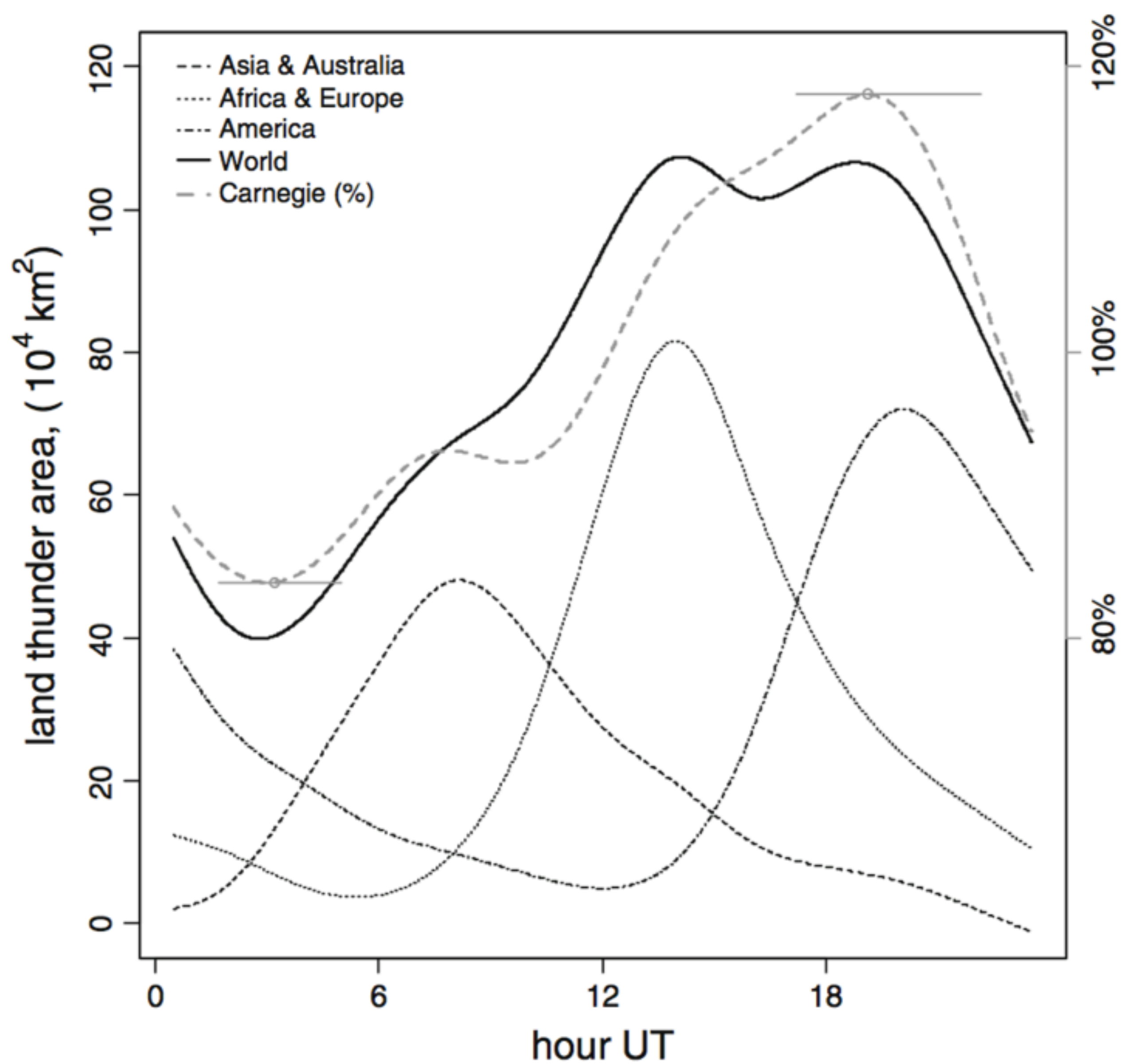


Fig. 11 Comparison between total land thunderstorm area (*thick solid line*, left-hand axis) with its regional contributions, as originally presented by Whipple and Scrase (1936), and the Carnegie curve (*grey dashed line*, right-hand axis) calculated as relative values from annual coefficients of Table 4. The seasonal range in timing of the Carnegie curve's maximum and minimum is shown by *horizontal bars* about their annual mean values

Harrison, 2013

Mach et al., 2011

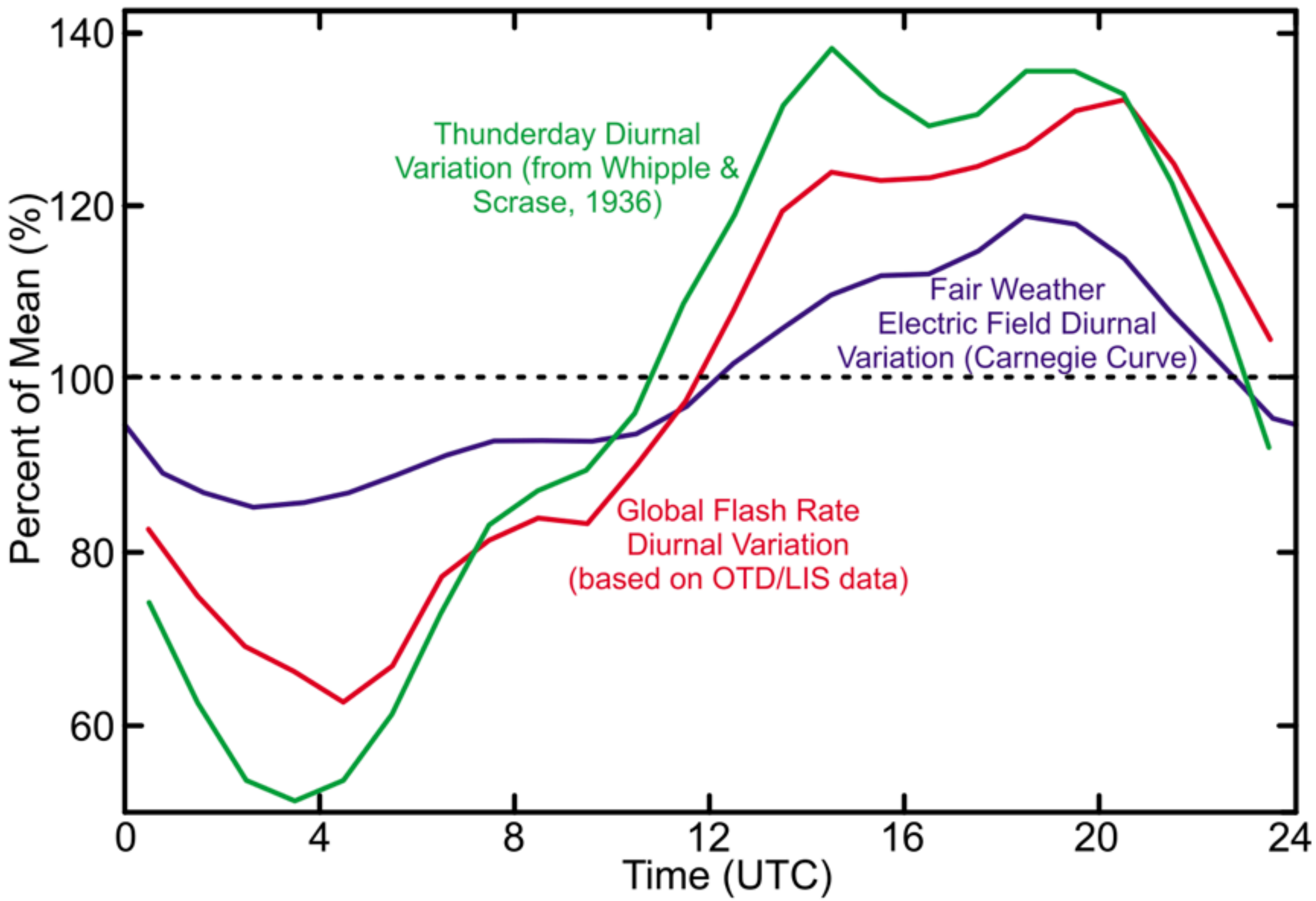


Figure 1. Diurnal variation of the fair weather field (blue curve) derived from ocean measurements (Carnegie curve), thunder day statistics (green curve) from *Whipple and Scrase* [1936], and diurnal variation of flash rates (red curve) derived from Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) data. Note that the phase and shape of the three plots are very similar, but the amplitudes are quite different.

Better way of counting lightning => better match

Including electrified showers => even better match

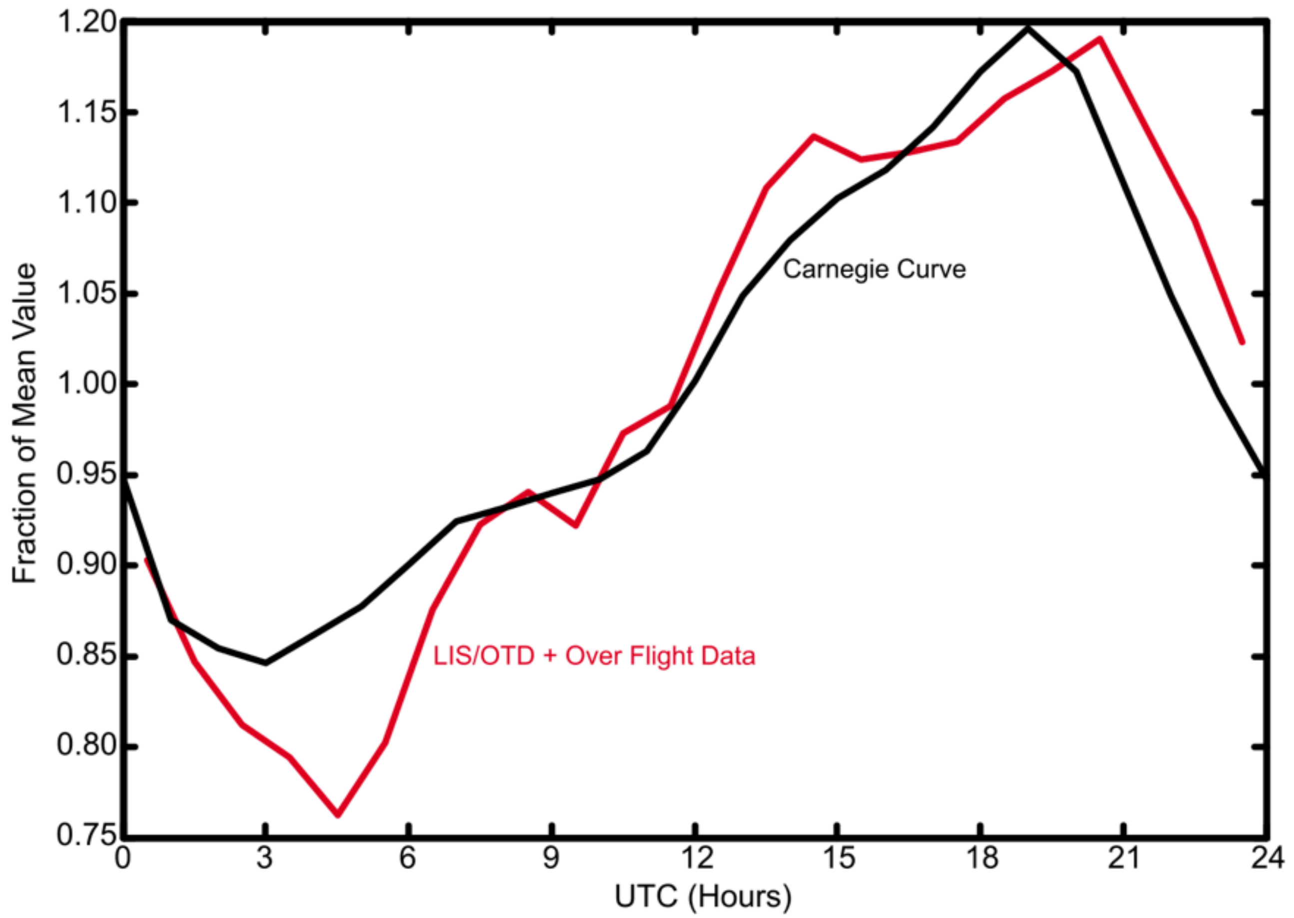


Figure 10. Comparison of the relative magnitudes of the Carnegie curve and total conduction (Wilson) current derived from LIS-OTD and our overflight data shown in Figure 8.

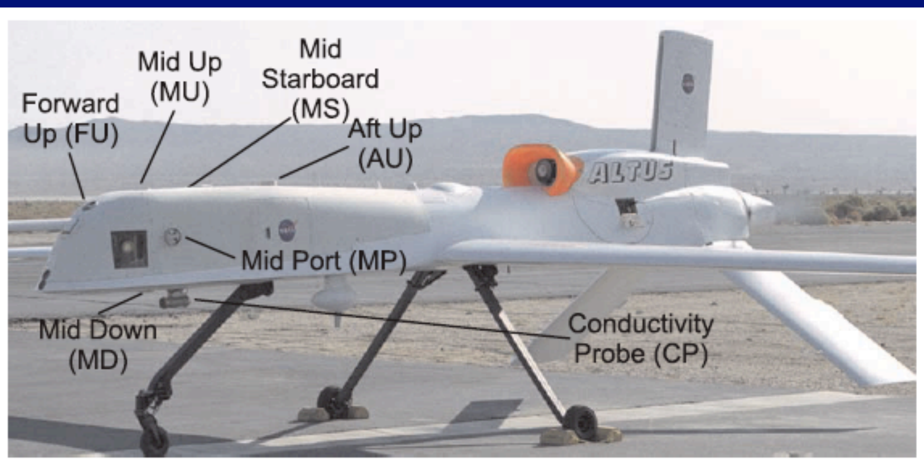


Figure 2. General Atomics Aeronautical Systems, Inc. (GA-ASI), Altus-II aircraft used in the Altus Cumulus Electrification Study (ACES), one of the field programs in this study. The locations of five of the six field mills are shown. The Mid Starboard (MS) mill is on the other side of the aircraft in the same general location as the Mid Port (MP) mill. The other mills are labeled Forward Up (FU), Mid Up (MU), Aft Up (AU), and Mid Down (MD). The conductivity probe (CP) is also shown. The Altus aircraft operates at a nominal altitu 5 km with a cruise speed of about 35 m s^{-1}.

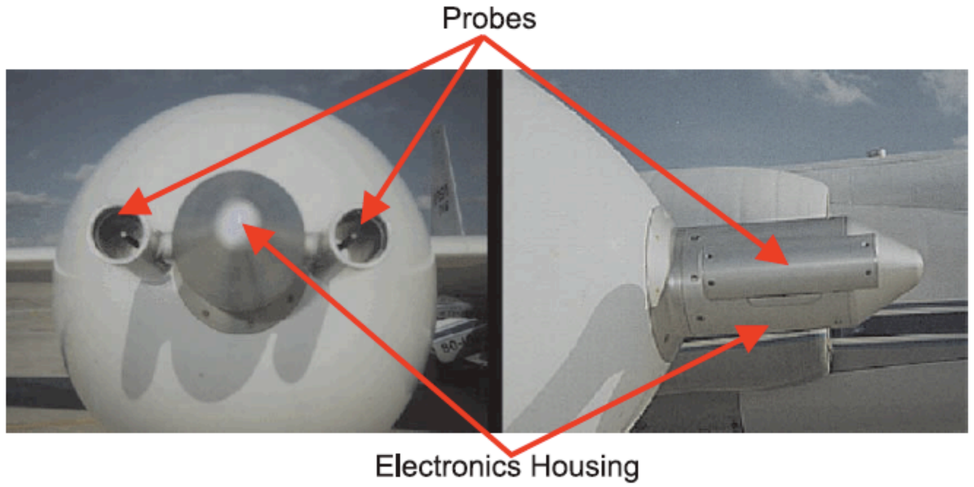
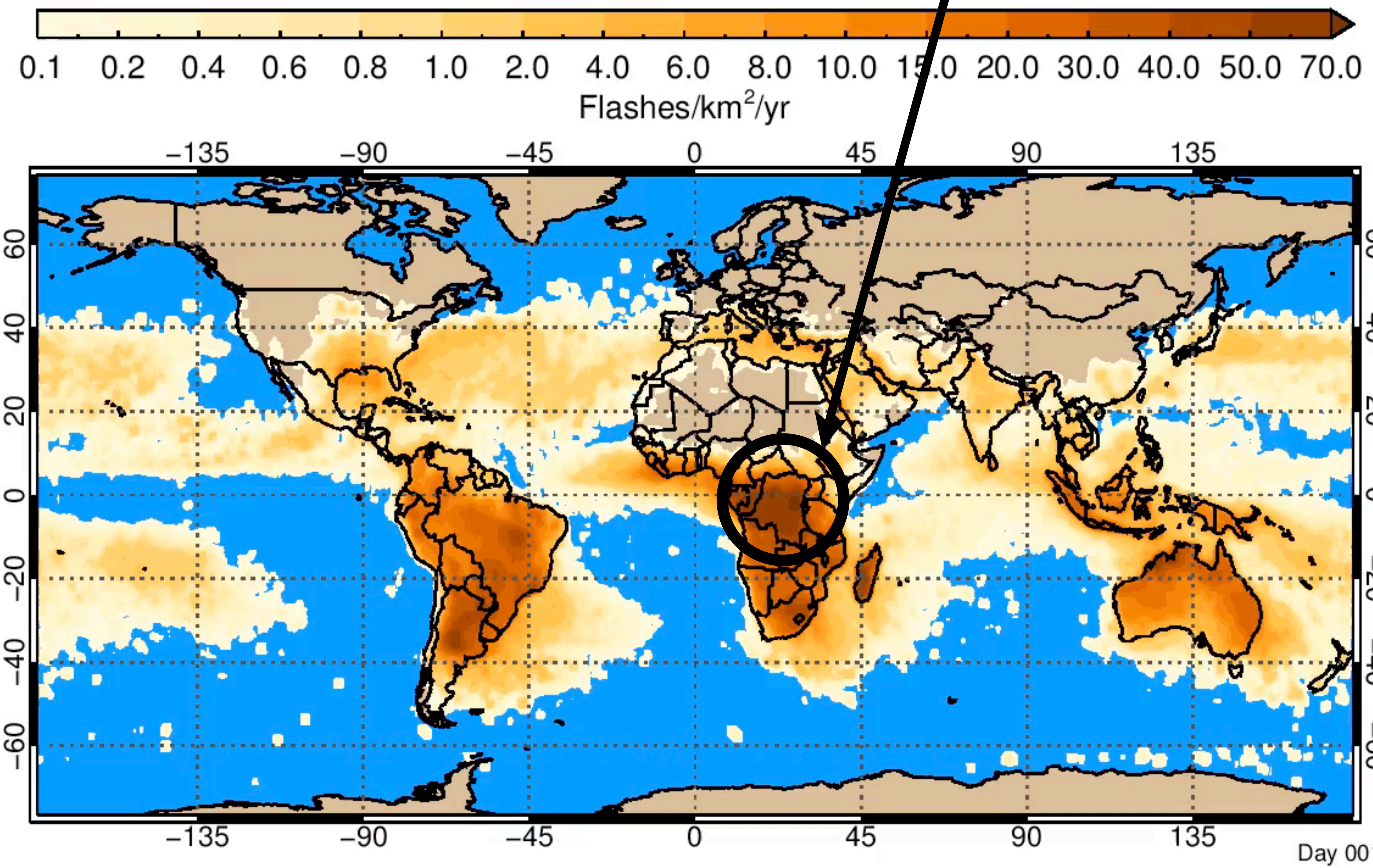


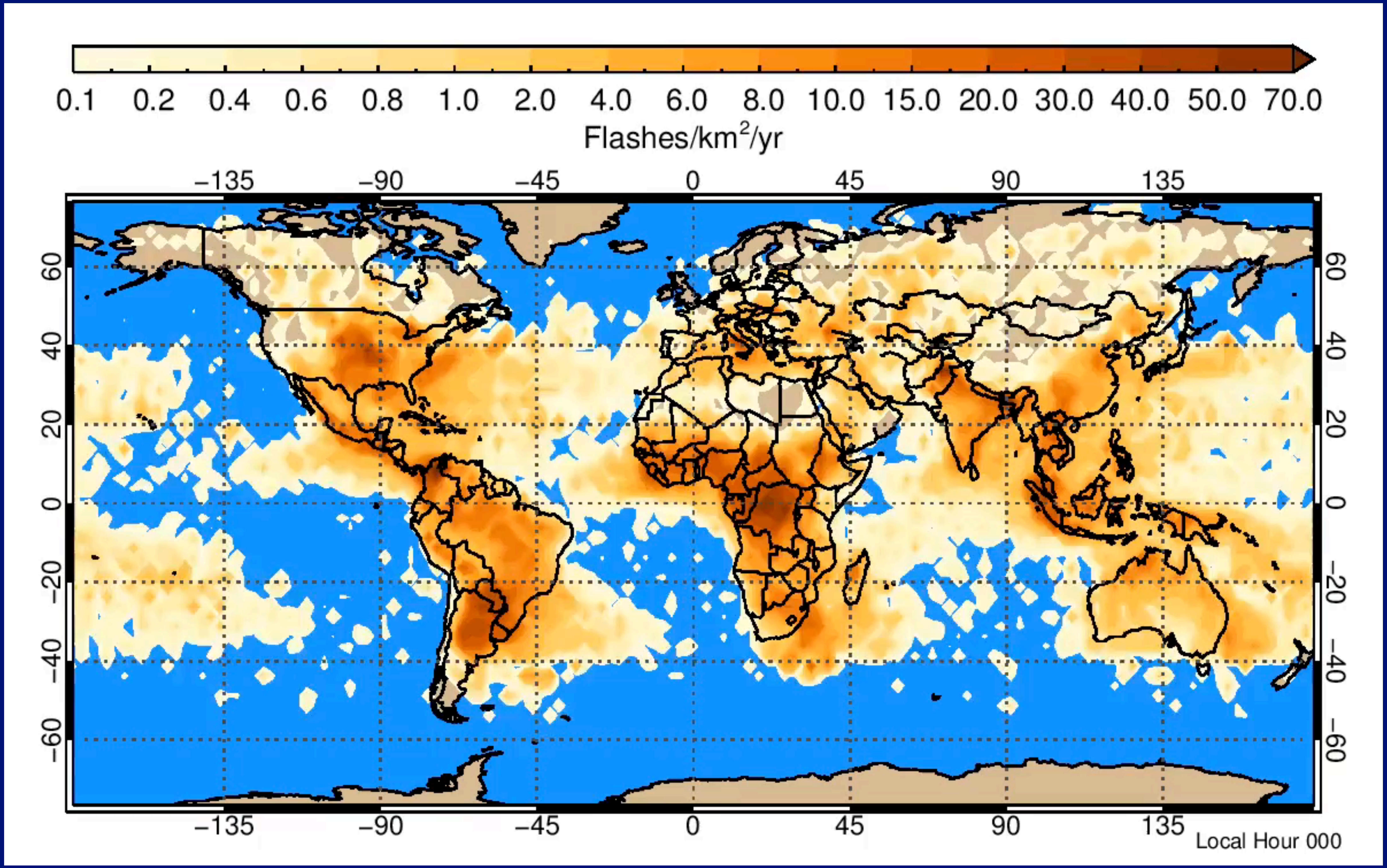
Figure 4. Picture of our dual conductivity probe. The two outer cylinders house the sensing probes that concurrently measure the conductivity contribution due to positive and negative ions. The central cylinder houses the electronics needed to process the signals into voltages that are proportional to the conductivity. The voltages a digitized and sent to the digital recorder along with the instrument status data.

How does lightning vary seasonally?

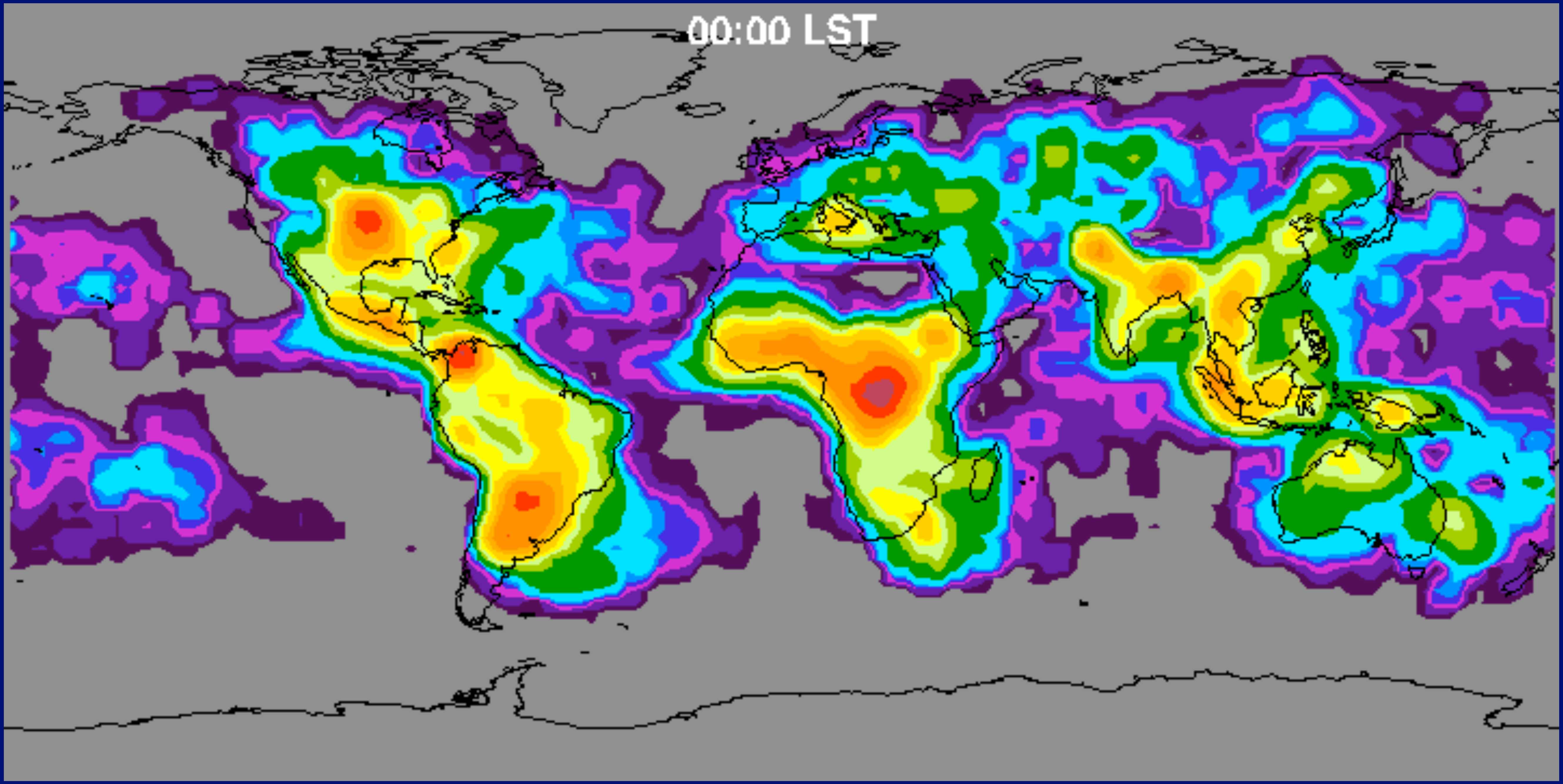
over 250 flashes per square mile per year!



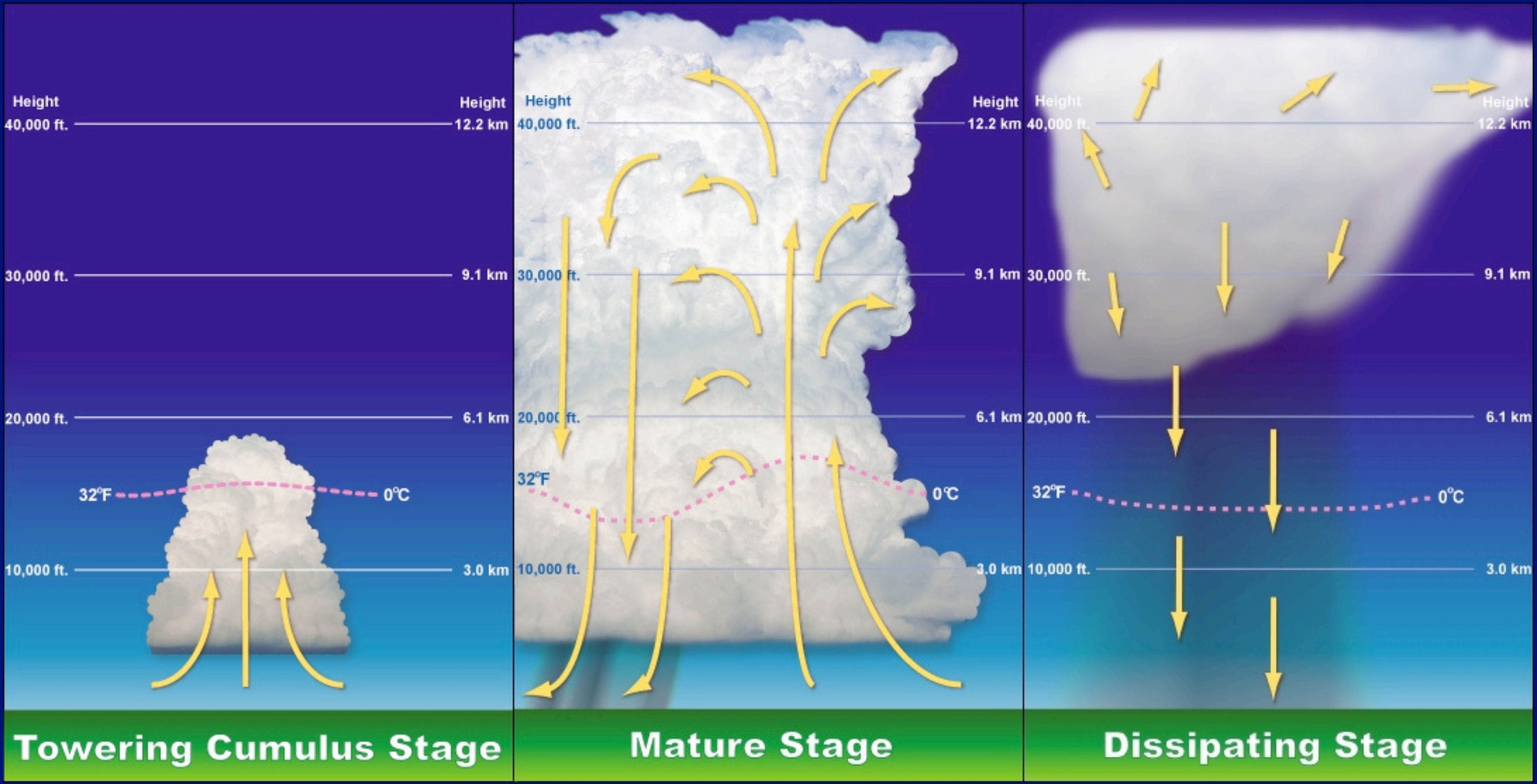
How about daily?



on average, there about 45 flashes occurring worldwide per second

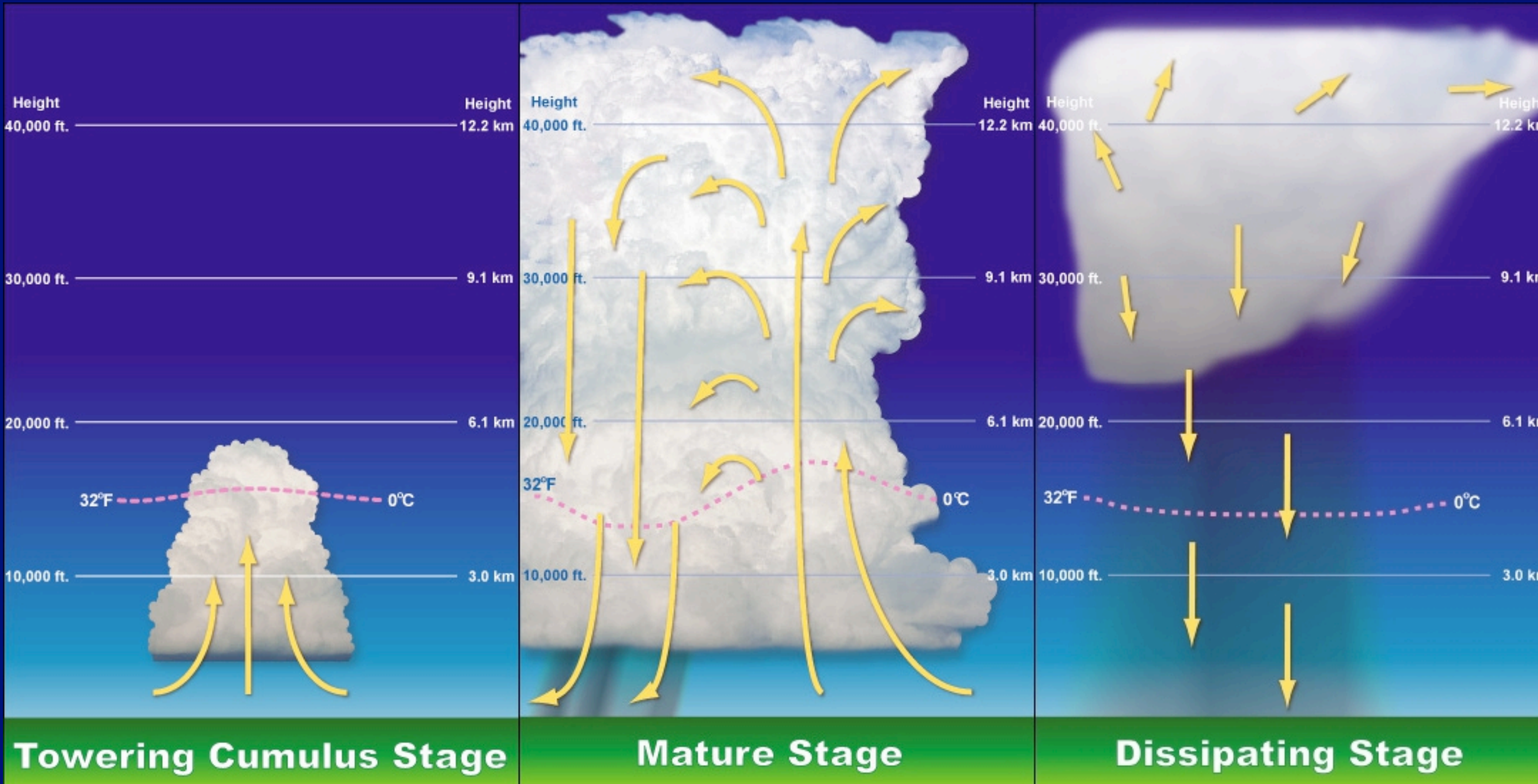

00:00 LST

How do storms even get electrified?



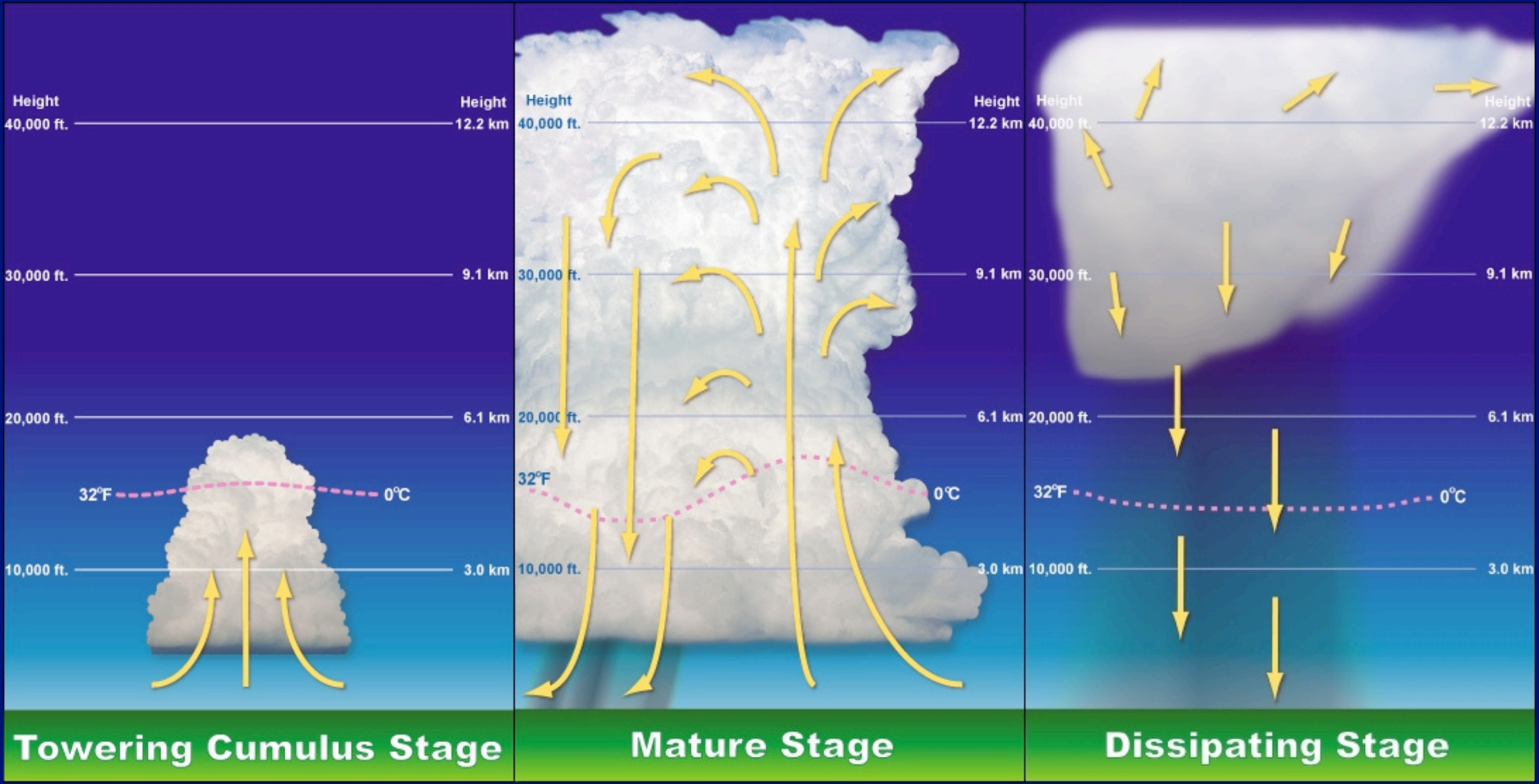
Adapted from Byers and Braham, 1949

cumulus stage: Updraft rises, and particles grow by condensation (and deposition). Eventually, some particles grow large enough so that they begin to fall. Downdrafts begin to form due to drag of falling particles and evaporation/ sublimation.



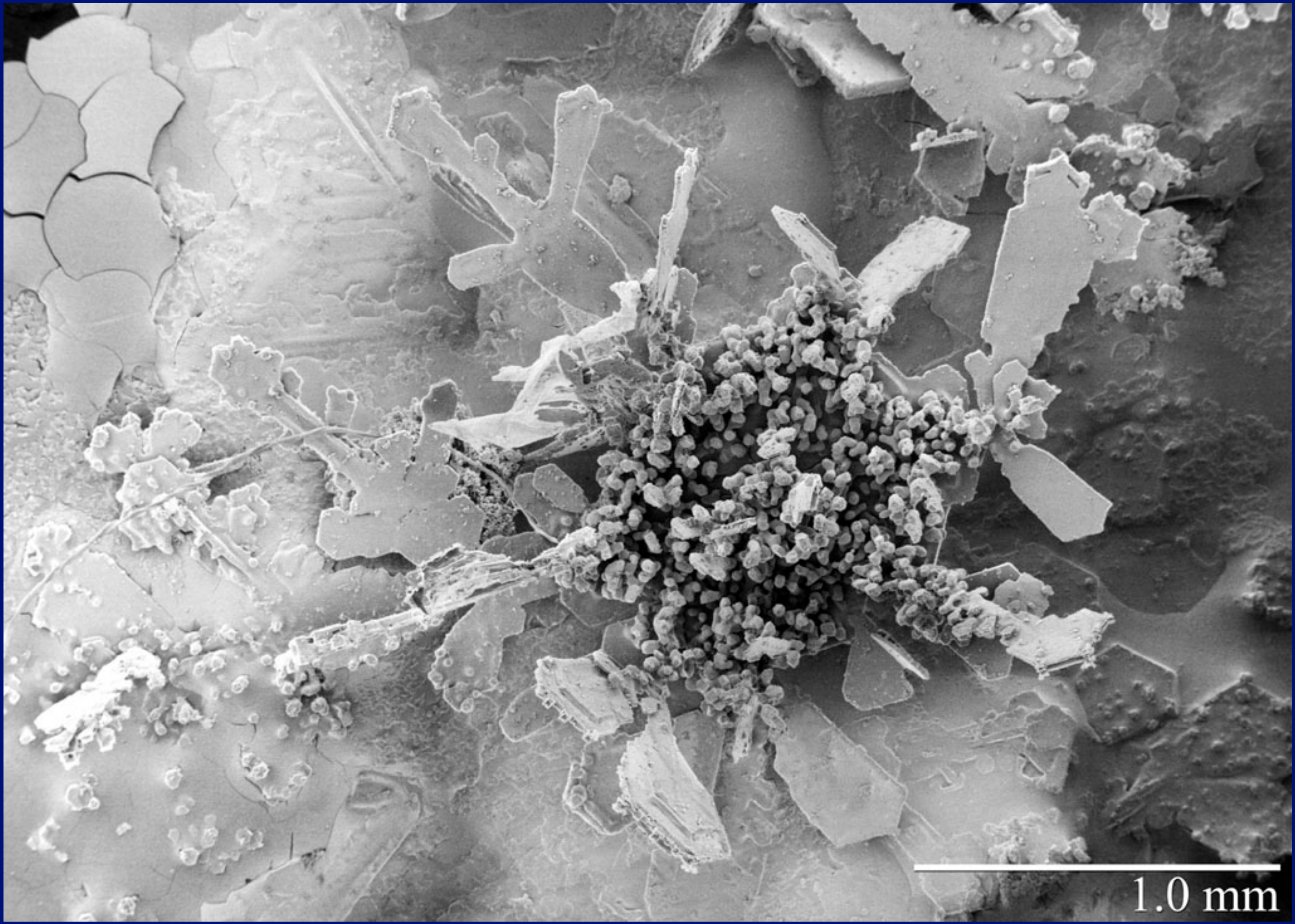
Adapted from Byers and Braham, 1949

mature stage: Precipitation reaches the ground. The updraft increases and cloud grows. Downdrafts extend horizontally and vertically. These reach the ground and produce a diverging wind flow.

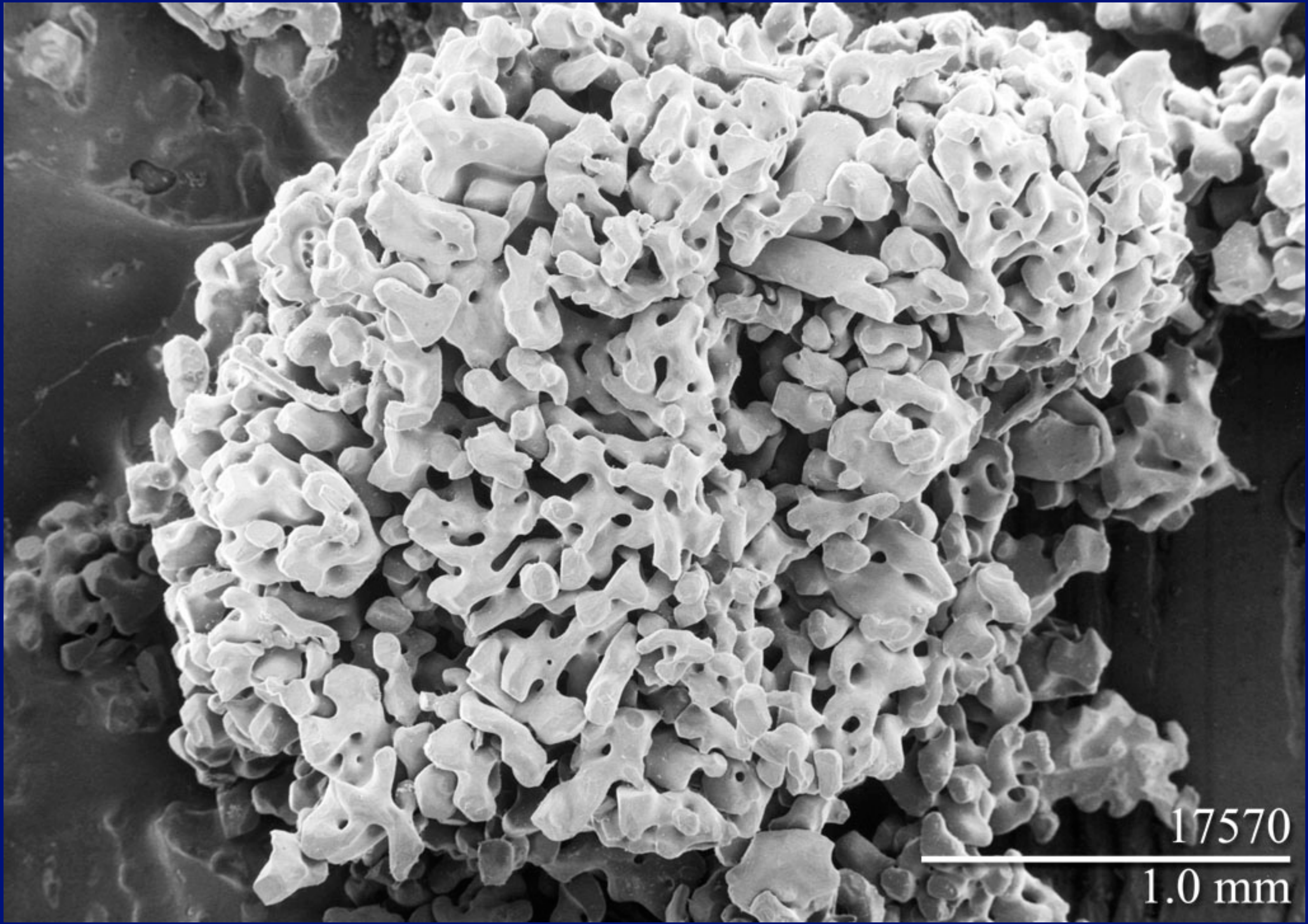


Adapted from Byers and Braham, 1949

dissipating stage: The area of downdraft completely extends across the cloud. The updrafts may continue, but are weak (and cut off). Precipitation slows and downdrafts weaken.



Supercooled water drops are riming on the ice crystal...



This is graupel - we can no longer discern the ice crystal

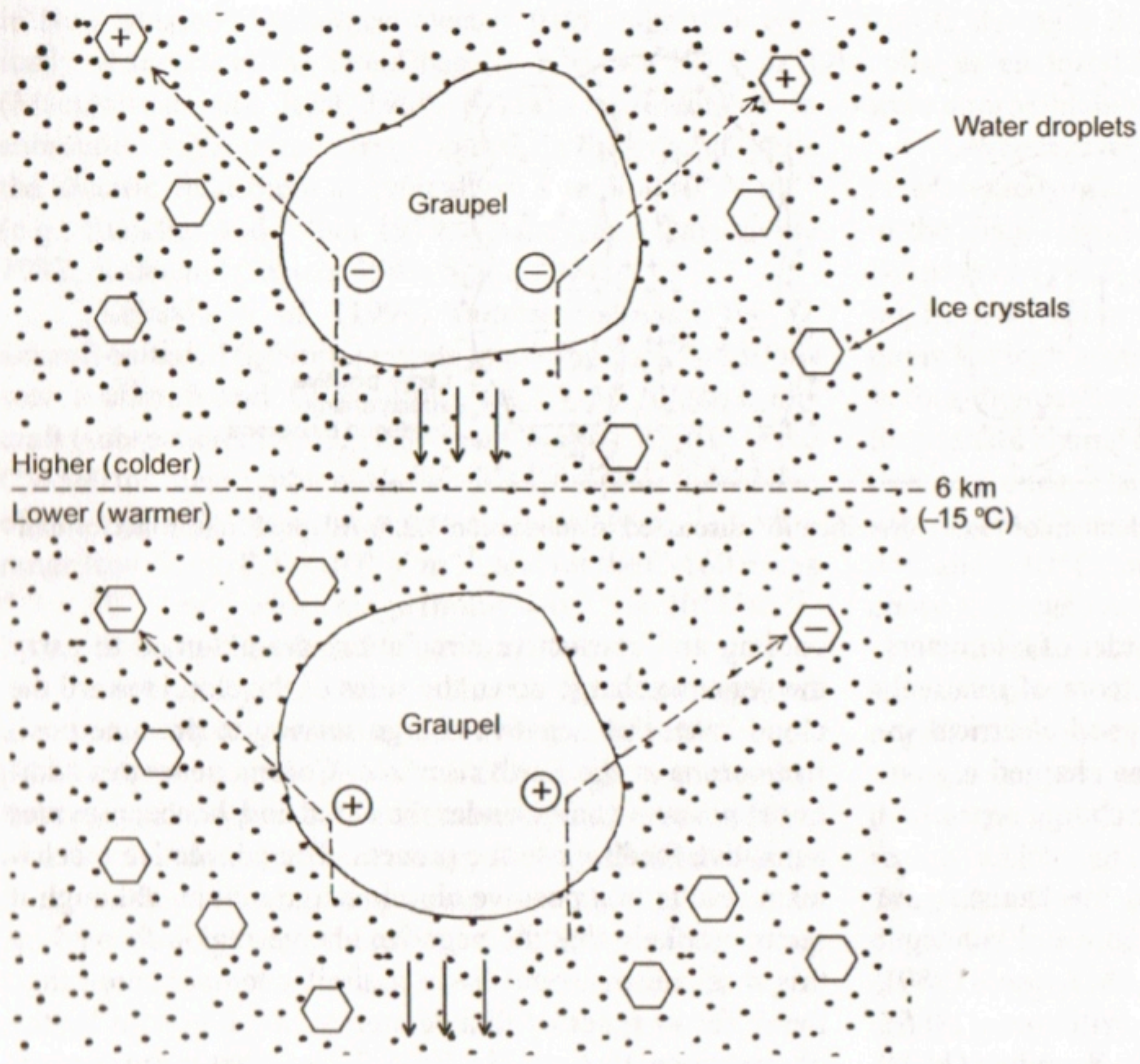


Fig. 3.13. Charge transfer by collision in the graupel–ice mechanism of cloud electrification discussed in subsection 3.2.6. It is assumed that the reversal temperature T_R is -15 °C and that it occurs at a height of 6 km.

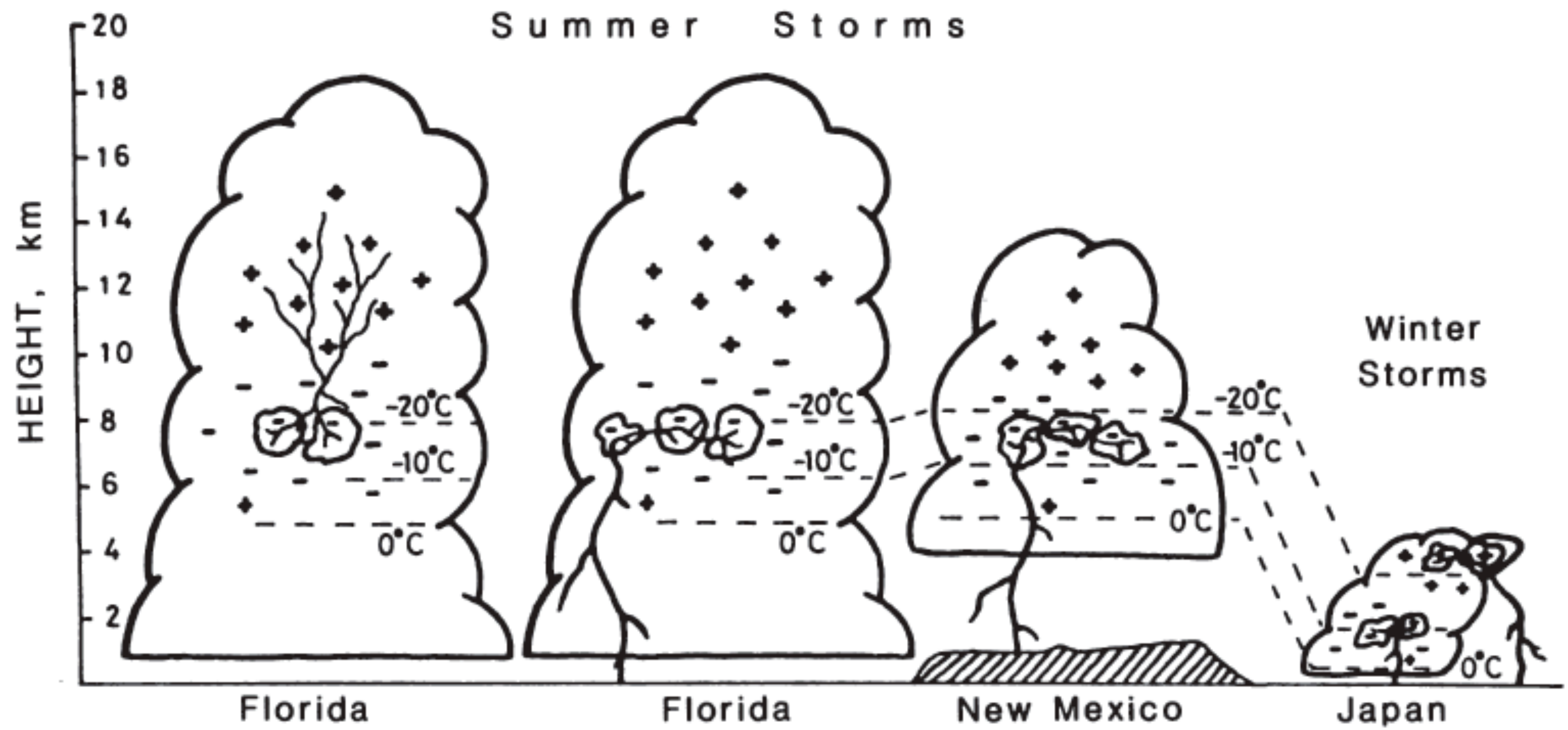


FIGURE 8.5 Illustration of how the negative-charge centers of cloud-to-ground lightning are at similar temperature levels in New Mexico and Florida storms, even though the latter have much greater extent of cloud and precipitation below the 0°C level and often above this level as well (adapted from the original by M. Brook, expressing the results of Jacobson and Krider, 1976; Krehbiel *et al.*, 1979; Krehbiel, 1981; Brook *et al.*, 1982). The negative charge centers of intracloud lightning are also at similar altitudes and temperatures even though intracloud discharges extend upward in the cloud rather than downward. Preliminary studies of lightning in Japanese winter storms suggest that the negative charge is at lower altitude but similar temperature values as in the summer storms.

Krehbiel, 1986

The positively charged ice and negatively charged graupel separate gravitationally...

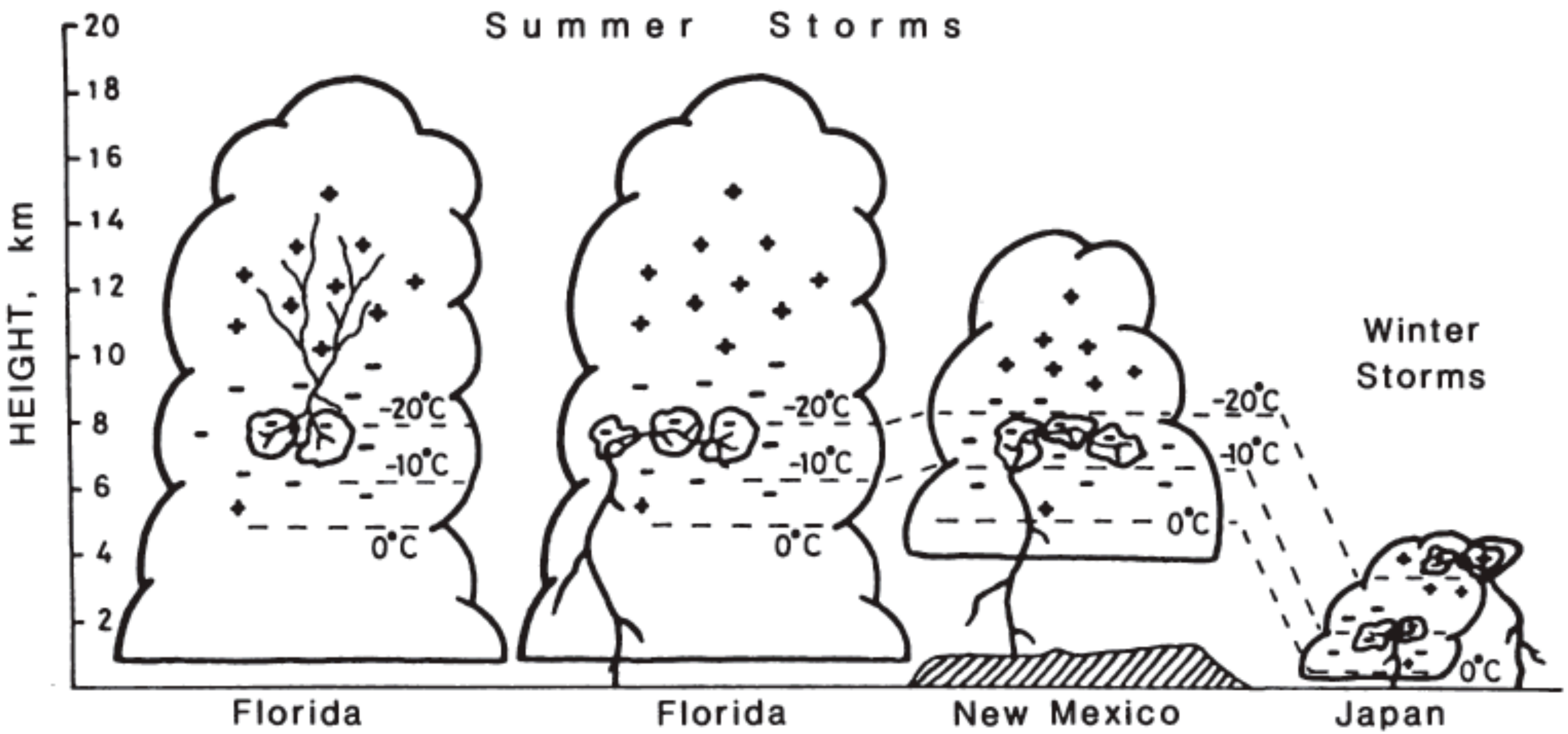


FIGURE 8.5 Illustration of how the negative-charge centers of cloud-to-ground lightning are at similar temperature levels in New Mexico and Florida storms, even though the latter have much greater extent of cloud and precipitation below the 0°C level and often above this level as well (adapted from the original by M. Brook, expressing the results of Jacobson and Krider, 1976; Krehbiel *et al.*, 1979; Krehbiel, 1981; Brook *et al.*, 1982). The negative charge centers of intracloud lightning are also at similar altitudes and temperatures even though intracloud discharges extend upward in the cloud rather than downward. Preliminary studies of lightning in Japanese winter storms suggest that the negative charge is at lower altitude but similar temperature values as in the summer storms.

Krehbiel, 1986

We commonly refer to the “tripole” structure of a thunderstorm

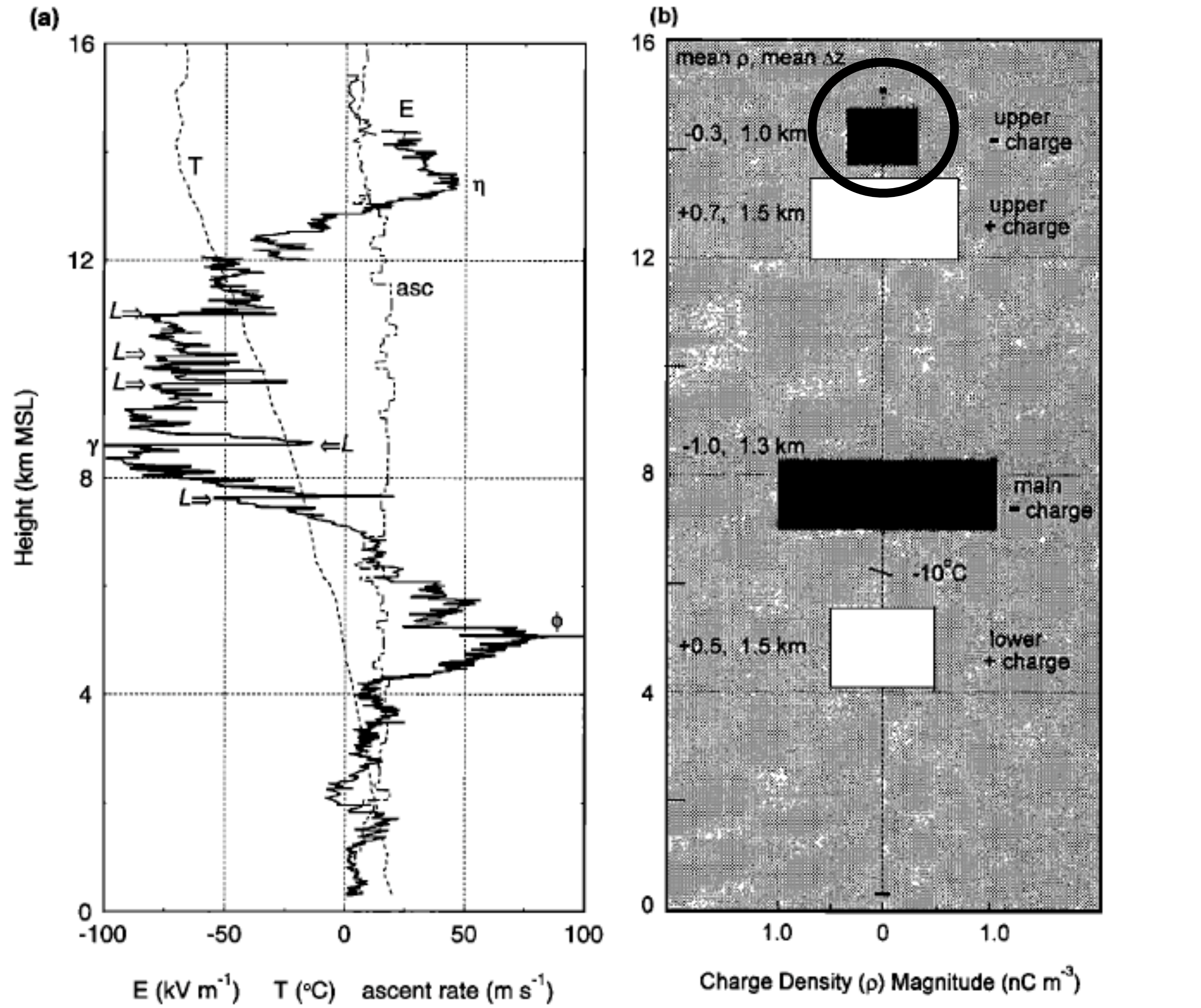
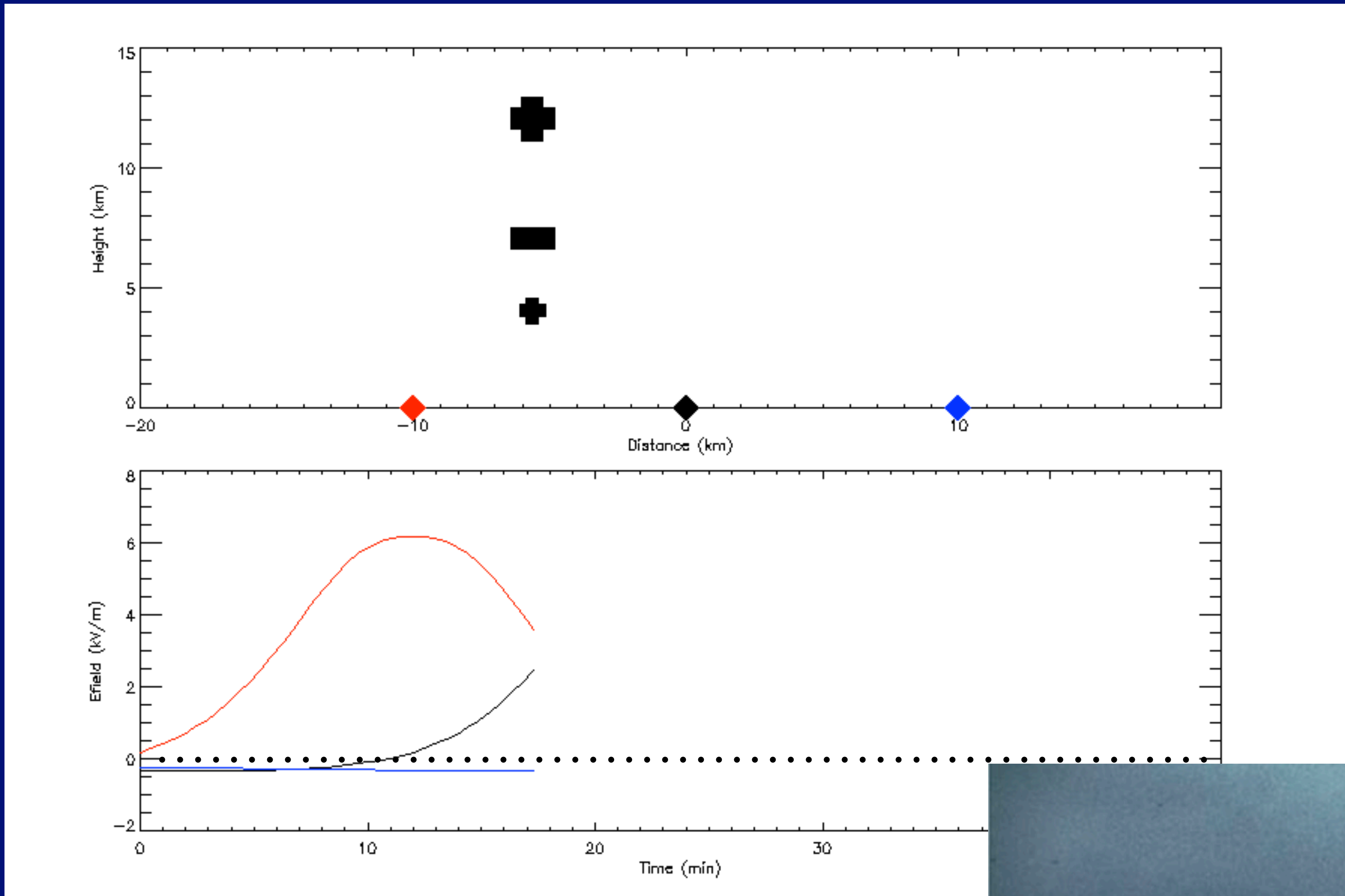


Figure 2. Basic electrical structure in updrafts of MCS convective regions. (a) Composite sounding of electric field (*E*), temperature (*T*), and ascent rate (asc). The composite has *E* data from the 91153 sounding (0-12 km), the 91143.1 sounding (12-14.5 km, after adding 3 km to heights), and the 87153 sounding (14.5-16 km). The *T* and ascent rate data are from the 94157.1 sounding (0-13.5 km) and the 90153 sounding (13.5-16 km). Three dominant features in the basic *E* structure are labeled ϕ (lower positive peak), γ (negative peak), and η (upper positive peak); four examples of lightning-related field changes are marked *L*. (b) Charge analysis from the *E* sounding using the one-dimensional approximation of Gauss's law. This is the basic charge structure in updrafts of MCS convective regions. Mean values of charge density (ρ) and depth (Δ*z*) of the charge layers for all the MCS updraft soundings are given, as are terms used in reference to each of the basic four charge regions. Negative charge regions are shaded black and positive charge regions are white.

Stolzenburg et al., 1998

The difference in conductivity for the atmosphere and cloud leads to a layer of charge at the boundary, ***the screening layer***



As a thunderstorm nears, the electric field changes sign at the ground....

and can be ~10kV/m under a storm

As the electric field at the ground increases, lightning danger increases!

Problem with lightning initiation:

ambient electric field measurements are roughly an order of magnitude smaller than dielectric breakdown field of air

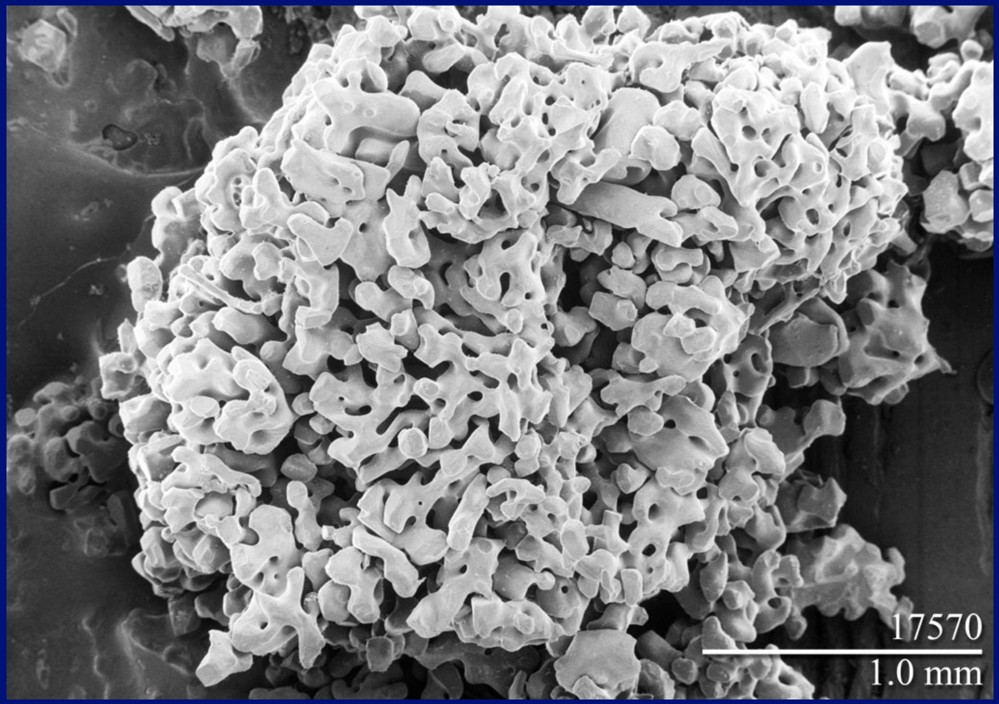
Problem with lightning initiation:

ambient electric field measurements are roughly an order of magnitude smaller than dielectric breakdown field of air

Hydrometeor Breakdown

↓

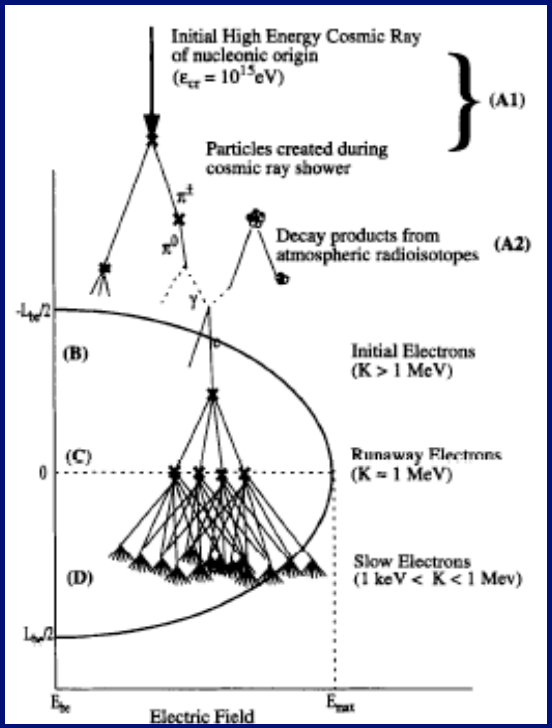
The ambient E-field is enhanced by hydrometeors
(rain drops, ice, graupel, etc.)



Relativistic Runaway Breakdown

↓

Energetic electrons are accelerated by the electric field and "runaway," leading to a region of enhanced conductivity, enhancing the E-field



Solomon et. al., 2001

Table C.1: Table summarizing the laboratory results of hydrometeor breakdown studies found in literature. The term "Standard Atmosphere" indicates that the pressure used depends on the temperature used, e.g., for $p = 700\,\mathrm{mb}$, $T = -10\,°\mathrm{C}$ and for $p = 400\,\mathrm{mb}$, $T = -30\,°\mathrm{C}$. The Schroeder et al. work showed that the electric field required to initiate streamers scales linearly with pressure.* The quoted electric field for the Coquillat et al. study are for horizontal electric fields; their results for vertical electric fields are similar to that of Schroeder et al.

Author(s), Year	Hydrometeor	Field (kV/m)	Pressure (mb)
Crabb and Latham, 1974 [16]	Warm Colliding Drops	250-500	1000
Blyth et al., 1998 [6]	Warm Colliding Drops	300-350	1000
	Supercooled Colliding Drops	300-350	1000
	Supercooled Drops and Ice Collisions	300	1000
Griffiths and Latham, 1974 [28]	Ice ($T < -12°C$)	350-500	500
Petersen et al., 2006 [65]	Ice ($0°C < T < -40°C$)	650-1000	850
	Ice ($0°C < T < -40°C$)	400-800	Standard Atmosphere
Schroeder et al., 1999 [76]	Modeled Drop Collisions	500-600	1000
Coquillat et al., 2003 [15]	Modeled Drop Collisions	110-290*	290-400

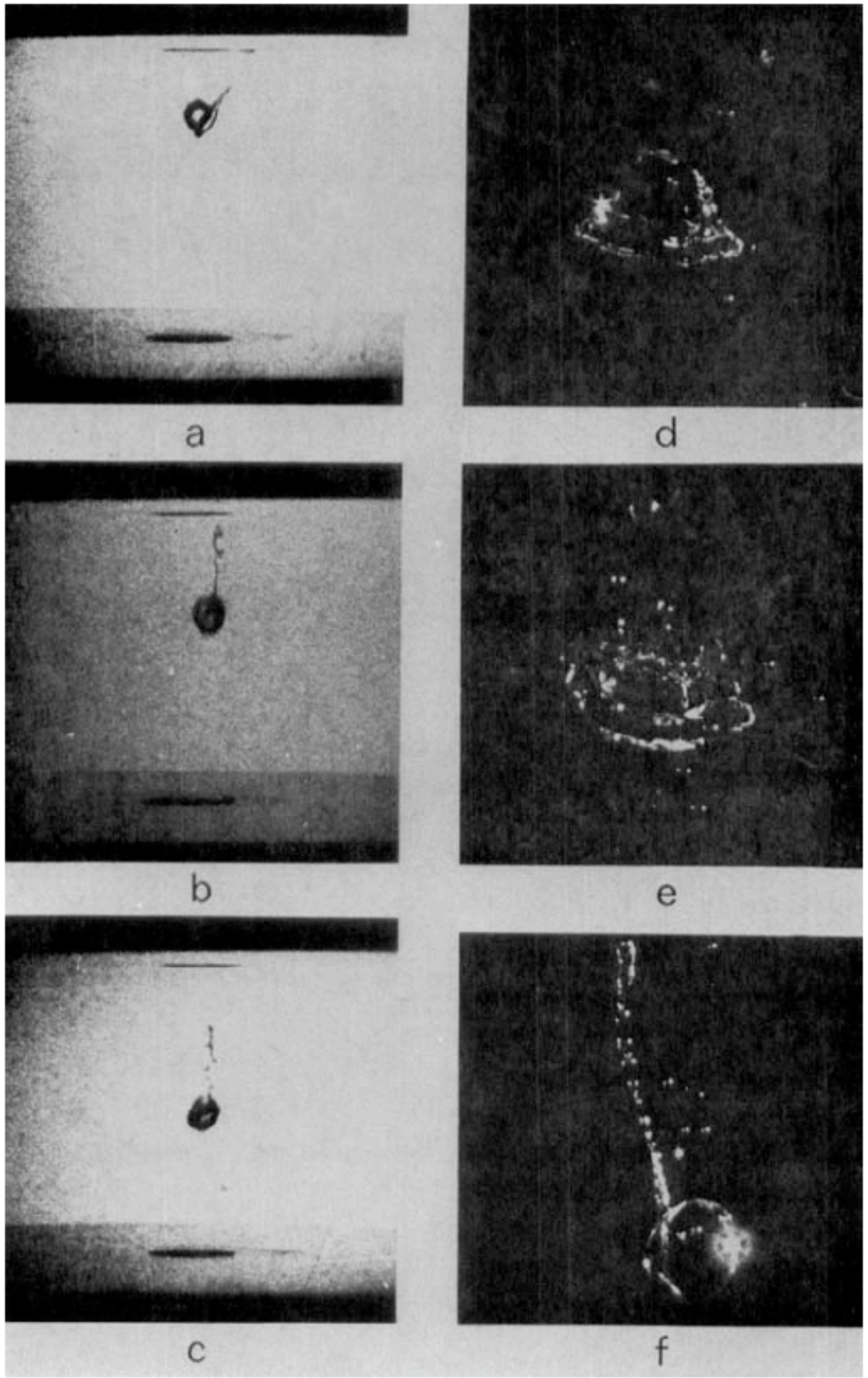
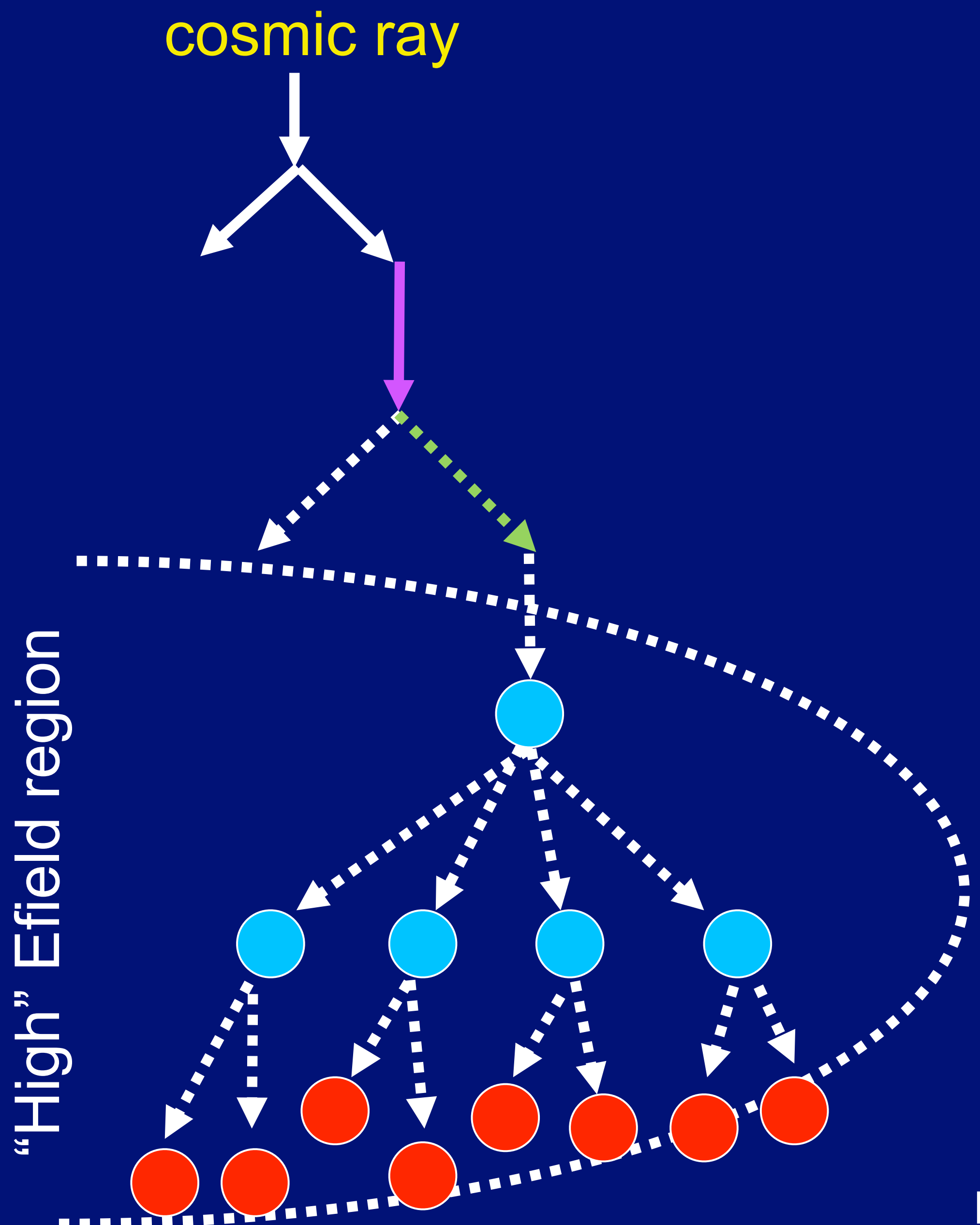


Figure 2. Various shapes assumed by drops of radius 2·7 mm colliding with ones of radius 0·65 mm with a relative velocity of 5·8 m s^{-1}. Photographs b, c, f: glancing collisions; e, d: head-on collisions; a: positioning at impact intermediate between the other two categories. Features on these photographs are discussed more fully in the text.

Crabb and Latham, 1974

Relativistic Runaway Breakdown



A high energy cosmic ray enters the atmosphere and collides with an atmospheric molecule, resulting in a number of particles, in particular, pions.

These pions decay, emitting gamma rays. These gamma rays impinge on atmospheric molecules, resulting in initial high energy electrons.

If the field exceeds the "breakeven field" over some distance L, then these new electrons can become runaways. They will collide with other molecules, producing even more high energy electrons.

In addition to the high energy electrons, numerous slow electrons are produced, but are unable to become runaways. The max concentration of these slow electrons occurs at the end of the high field region. This is thought to yield the plasma region responsible for lightning.

However...

there are far too few cosmic rays of sufficient energy to account for measured flash rates (Dwyer, 2010)

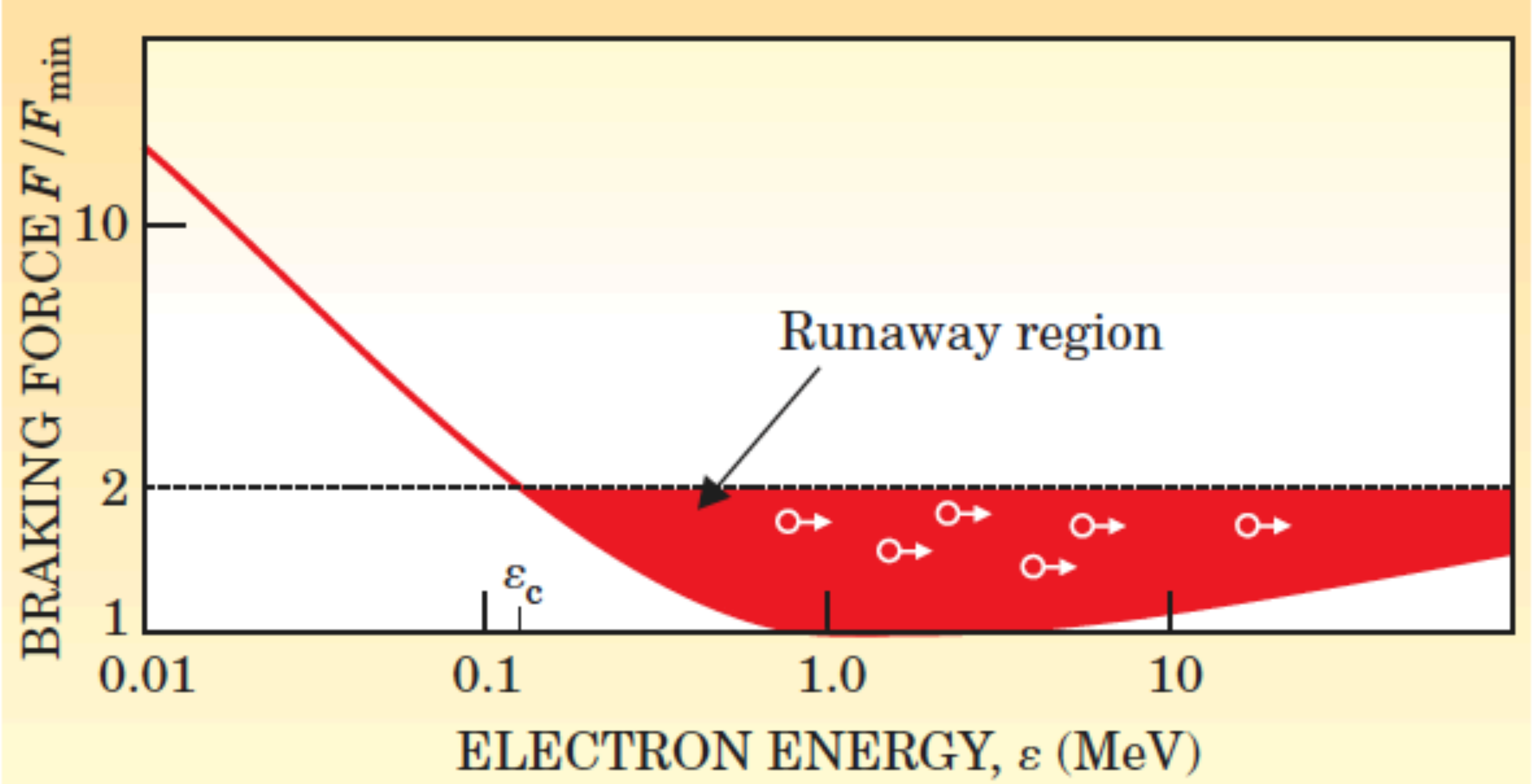
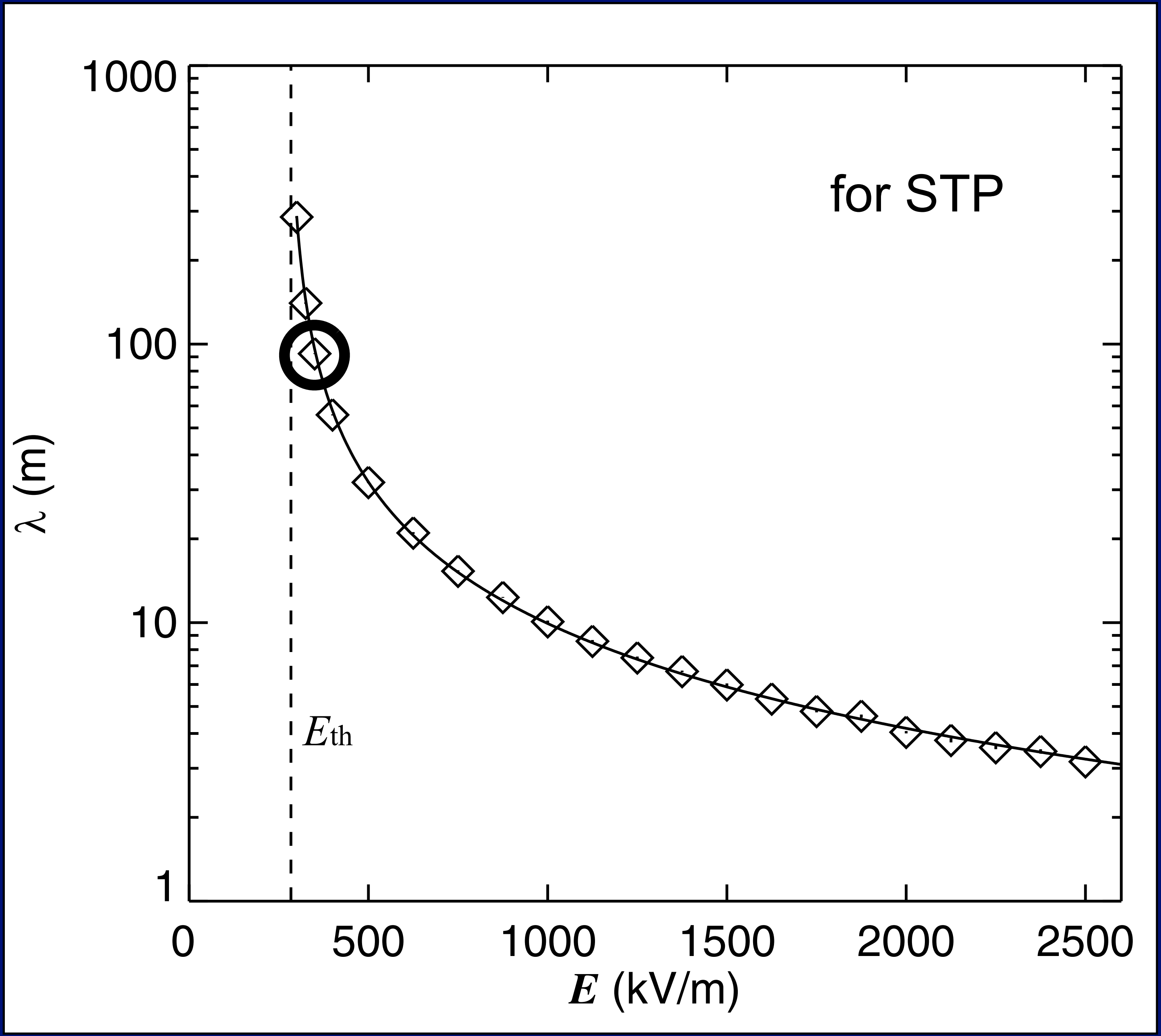


Figure 2. An electron loses energy as it ionizes atoms or molecules on its passage through matter. That braking force decreases with increasing electron energy until relativistic effects set in. With an electric field present, electrons above a certain critical energy ε_c can undergo runaway acceleration, shown schematically in the shaded region for an electrical field that is twice the critical field, $E = 2E_c$. The finite minimal braking force is $F_{min} = eE_c$.

Gurevich (1999) predicts that initiation via RRB would produce wideband radiation prior to VHF radiation...



Dwyer, 2003

Assume:

initiation height of 6km

electric field of 175 kV/m

Implies:

avalanche length is ~200m

total length of the high field region is ~2km

Further, Coleman and Dwyer (2006) show that the avalanche progresses with a speed of 0.89c

The modeling work provides a *testable* parameter if relativistic runaway breakdown is responsible for initiation:

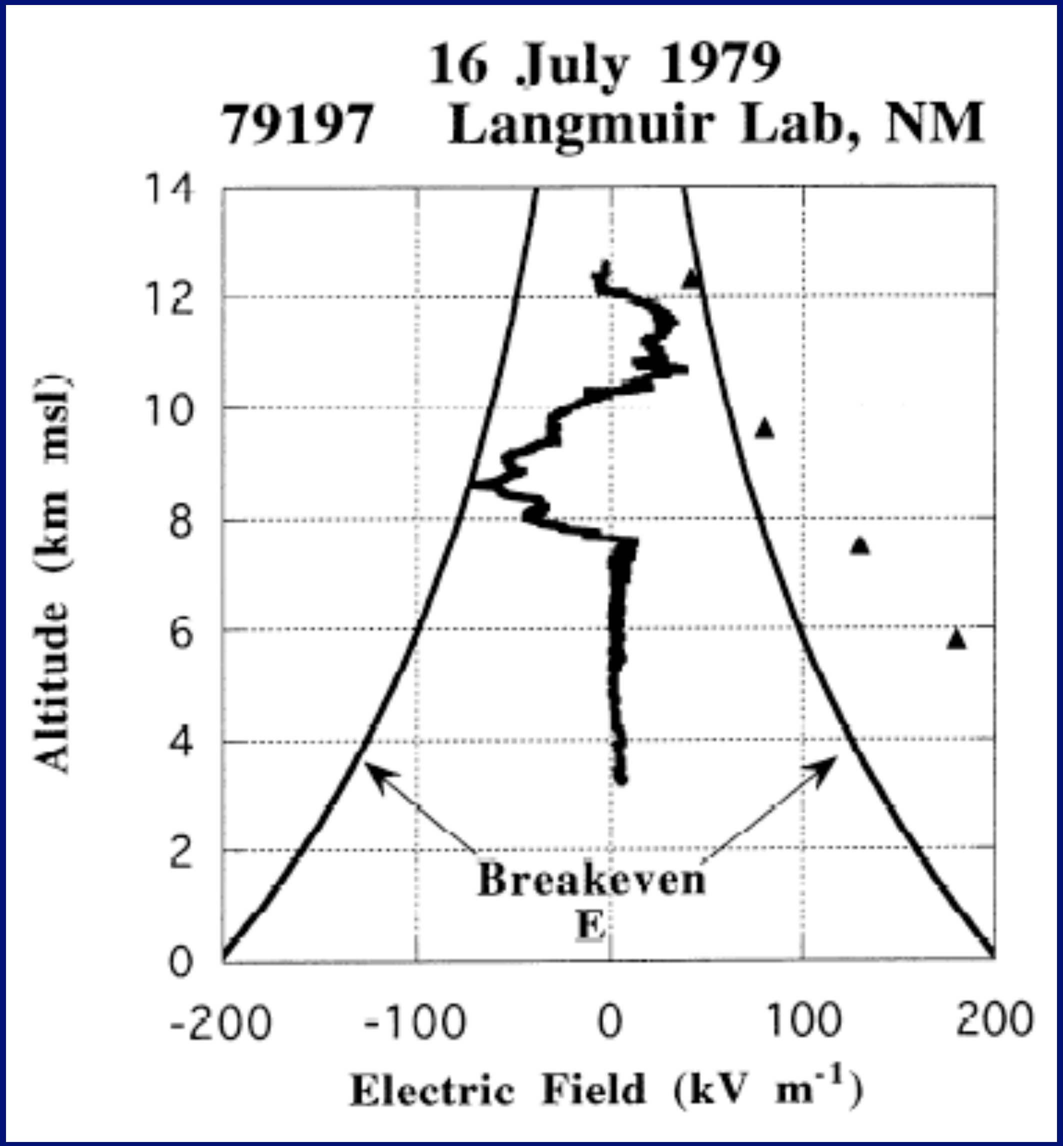
Model	~7.5μs	Dwyer, 2003
Measurement	685μs	Bitzer, 2011

Measurements of time lag between initiation in wideband and VHF are incompatible with RRB!

Further....

simulations (Dwyer, 2010) show the region of slow electrons is far too diffuse to yield the required conductivity.

What about hydrometeor breakdown?



Marshall et al., 1995

Critique of HMB:

measured electric fields are a factor of 2-5 too small

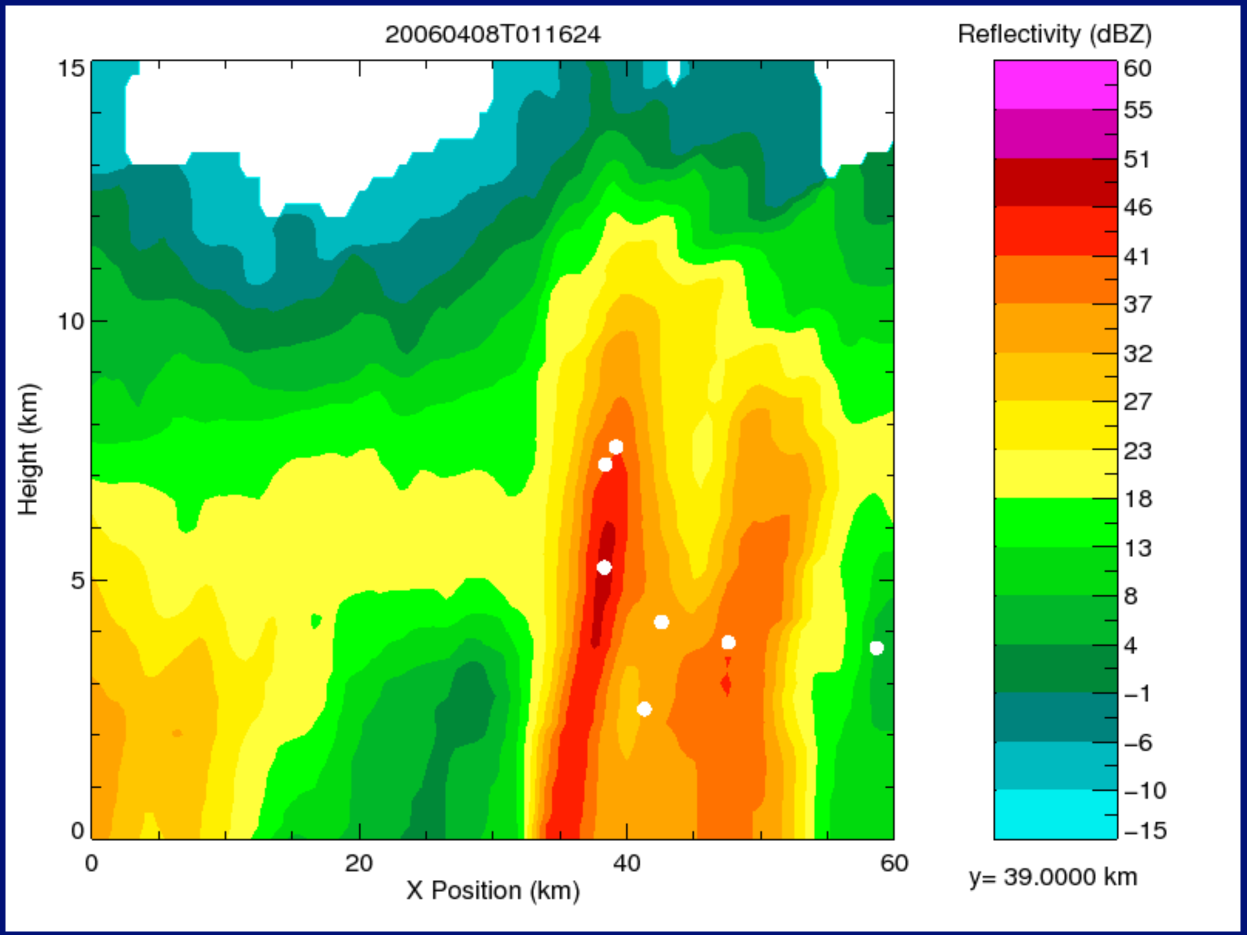
	Hydrometeor Type	Electric Field
Crabb and Latham, 1974	Colliding Drops	250-500
Blyth et al., 1998	Supercooled Colliding Drops	300-350
Petersen et al., 2006	Ice	400-800

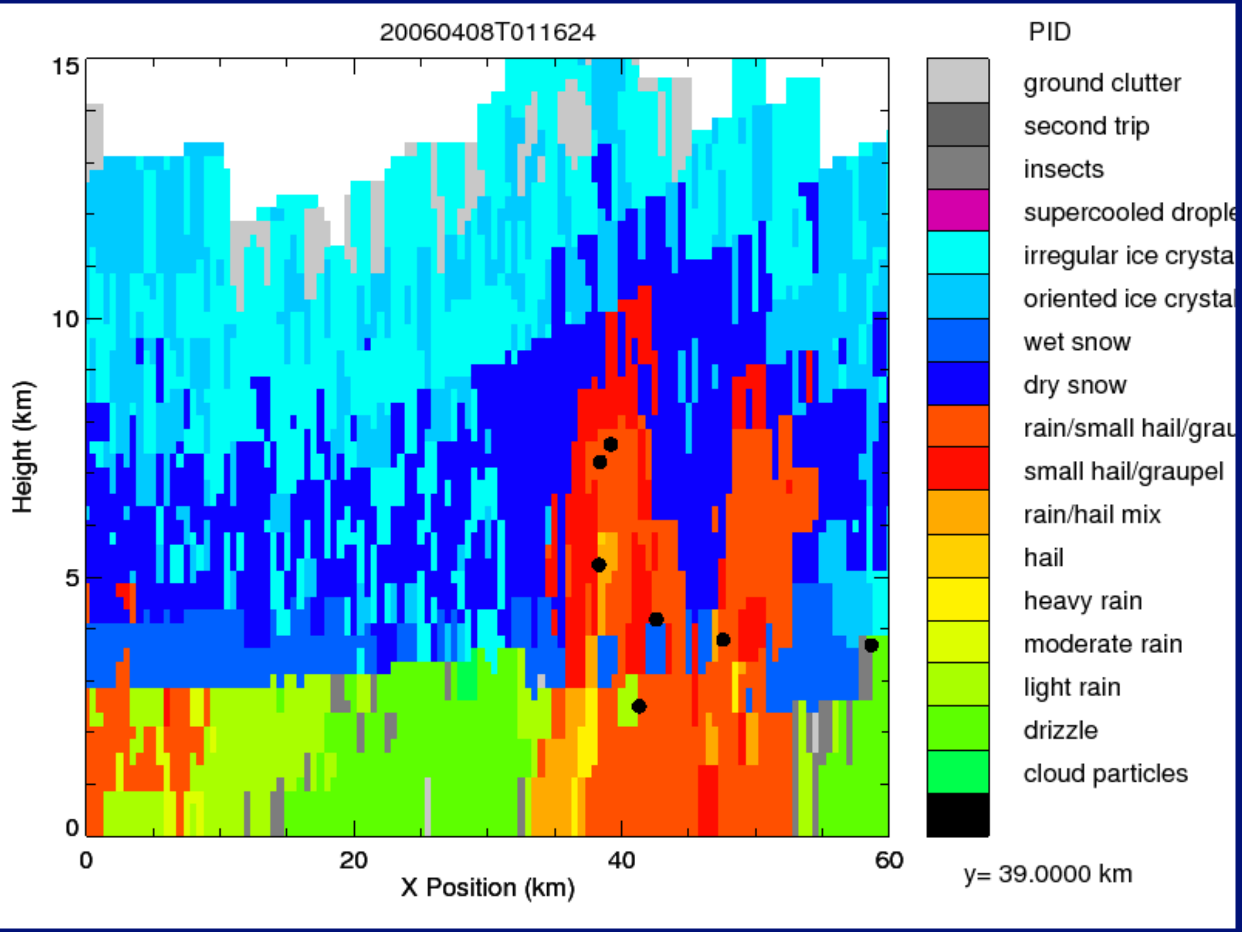
However, this critique largely ignores the required electric fields for HMB only need to exist over relatively short spatial scales!

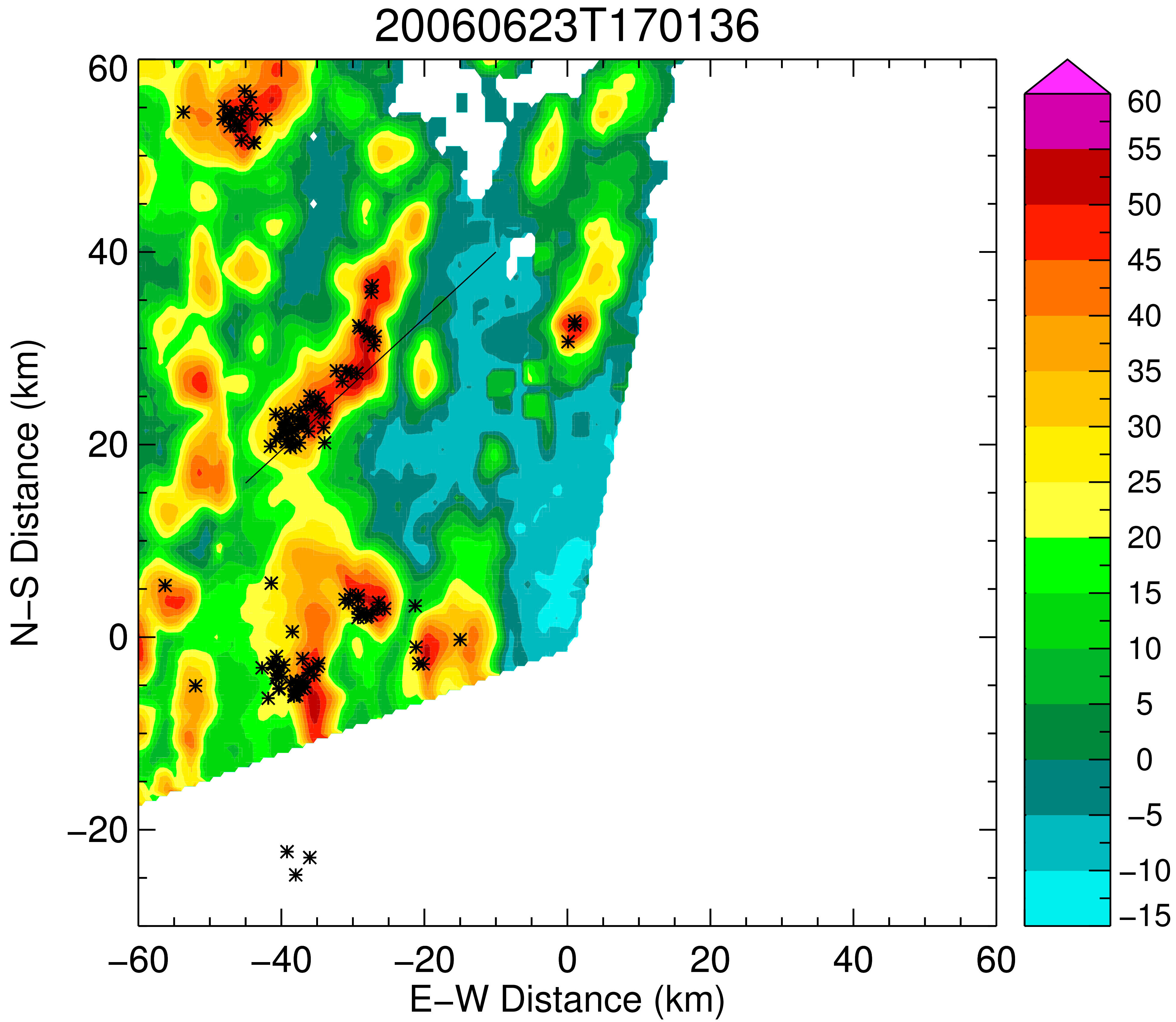
Is initiation correlated to hydrometeors?

ARMOR
Advanced Radar for Operational and Meteorological Research

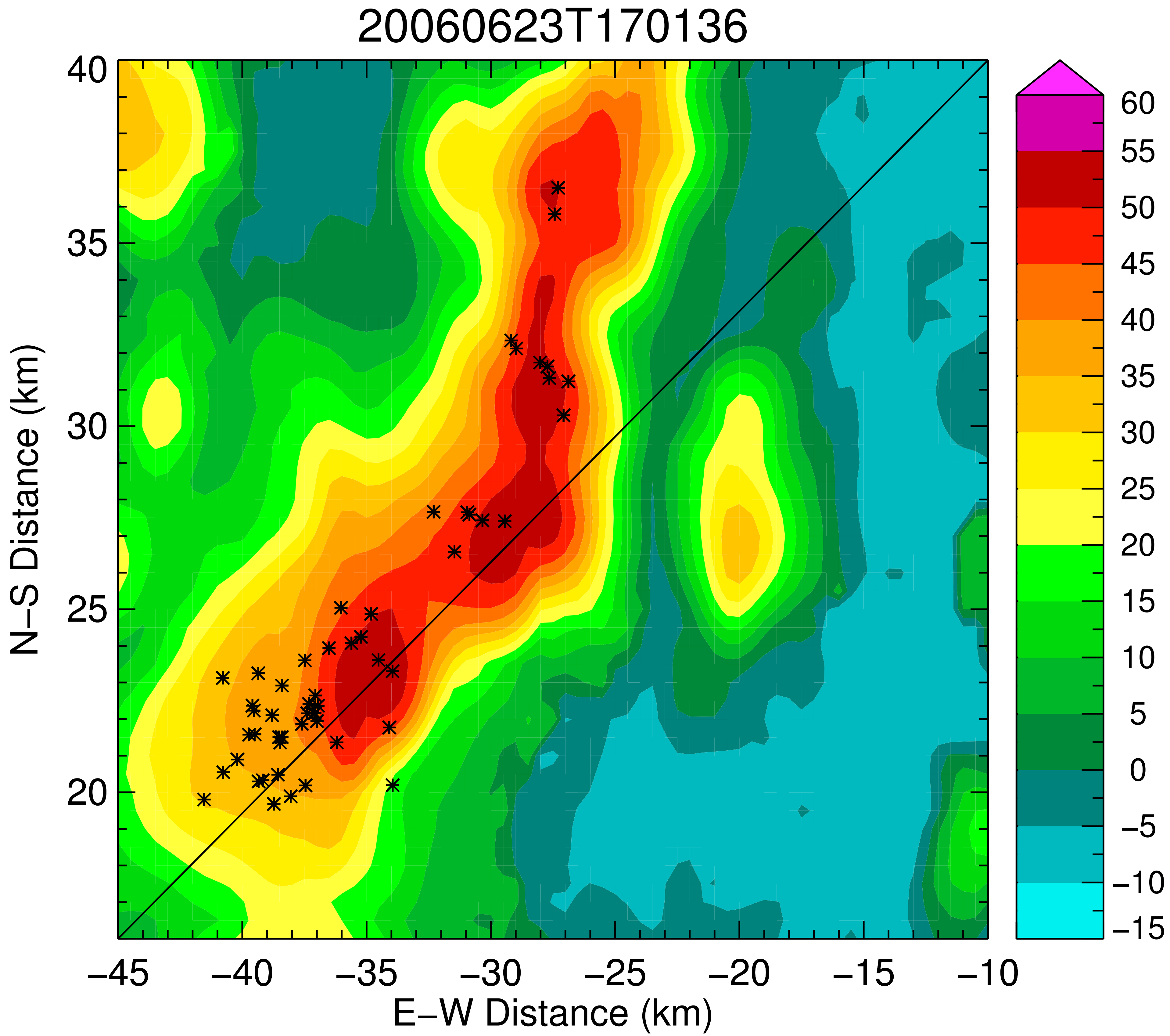
Using a "dual-pol" radar, hydrometeor environments in a cloud can be found



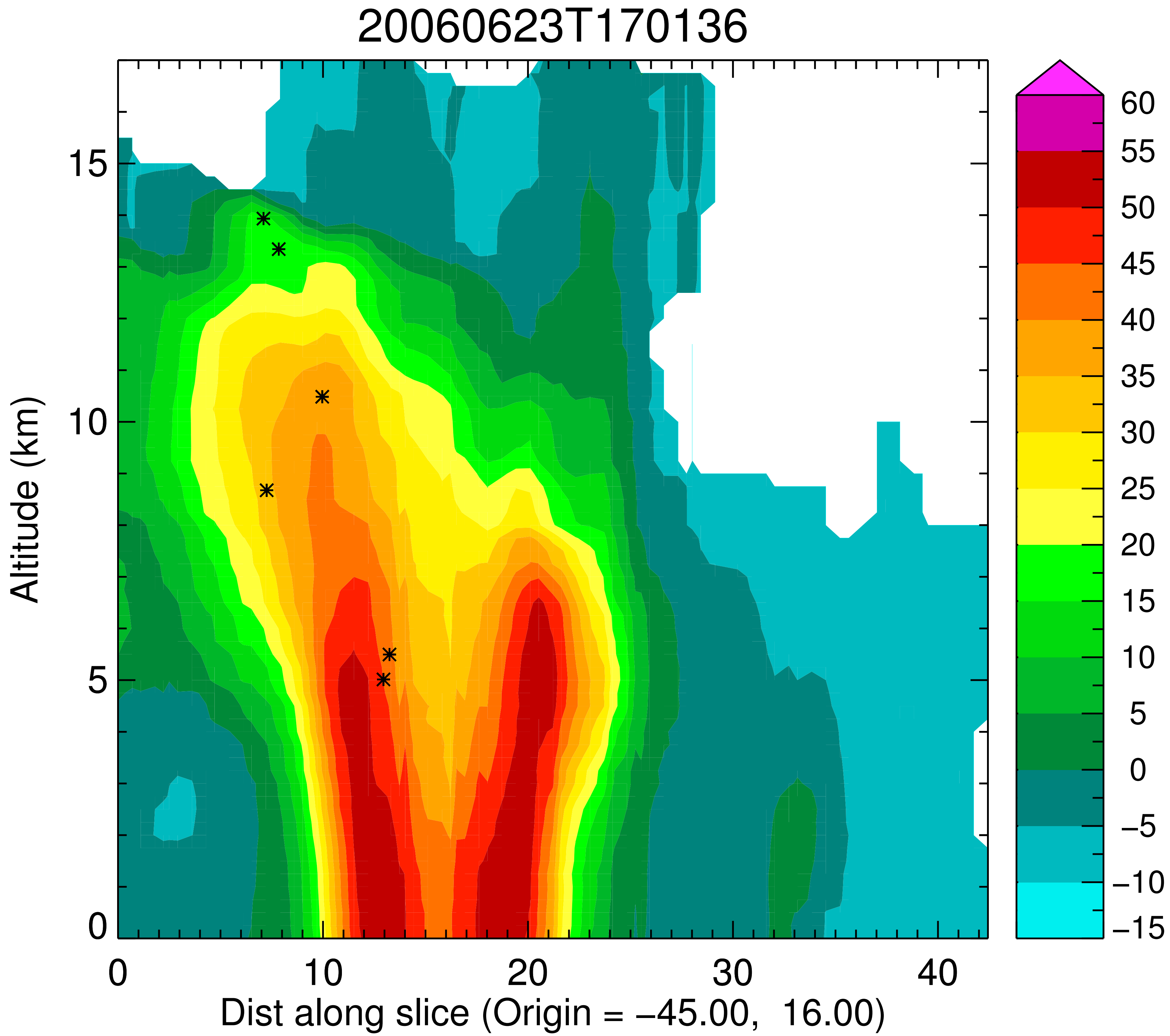




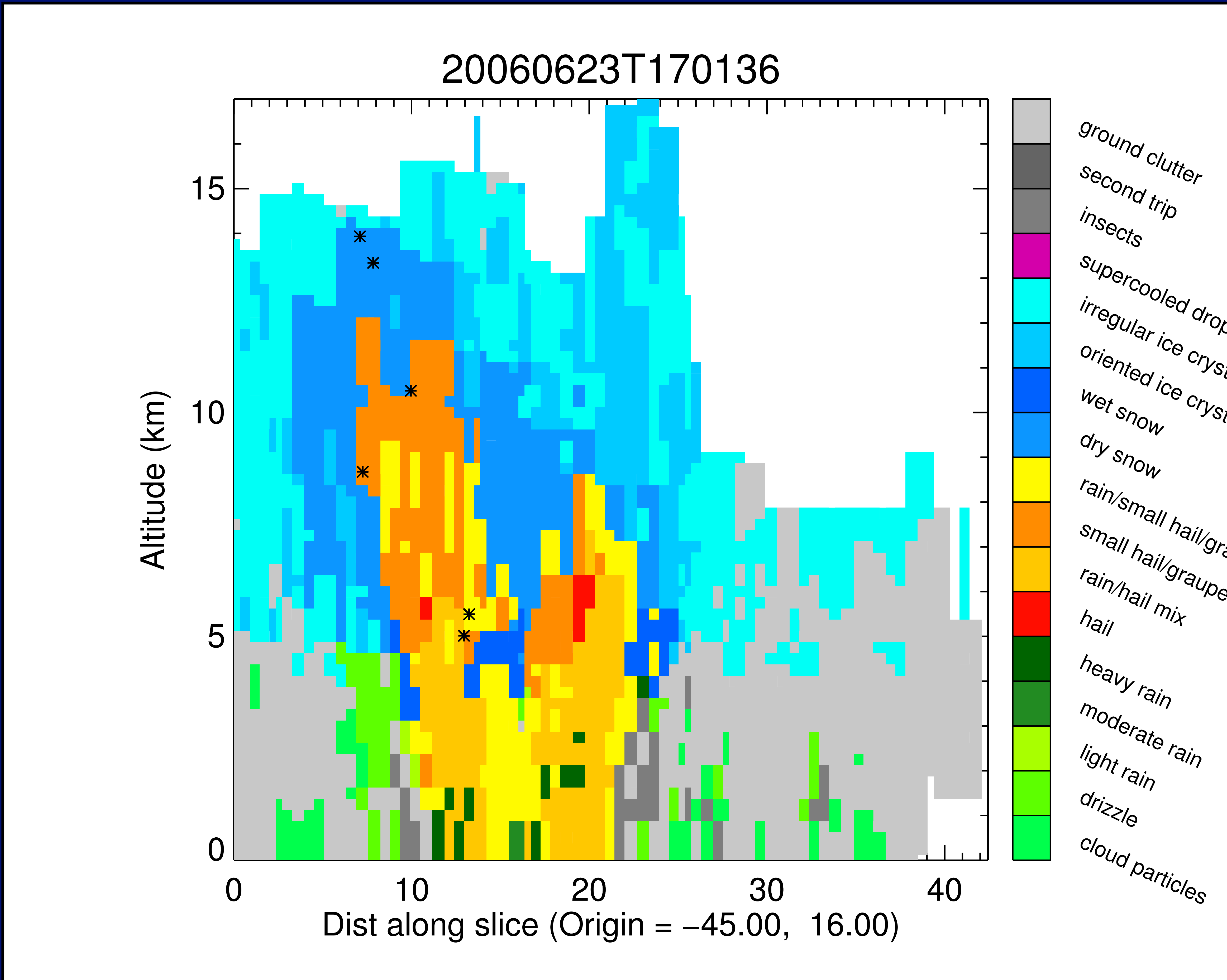
20060623T170136
N–S Distance (km)
E–W Distance (km)
60
40
20
0
–20
–60
–40
–20
0
20
40
60
60
55
50
45
40
35
30
25
20
15
10
5
0
–5
–10
–15

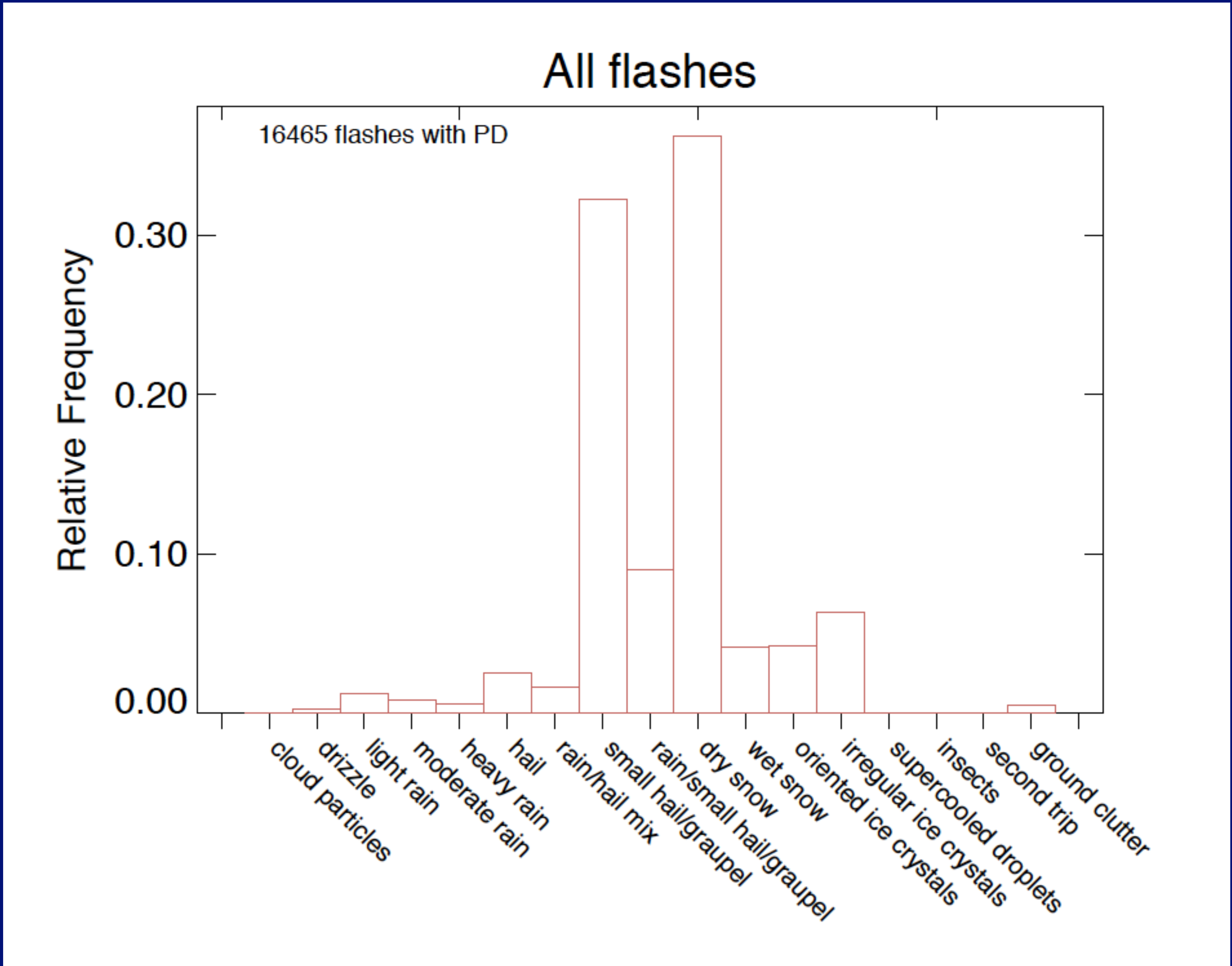


20060623T170136
N–S Distance (km)
E–W Distance (km)
40
35
30
25
20
–45
–40
–35
–30
–25
–20
–15
–10
60
55
50
45
40
35
30
25
20
15
10
5
0
–5
–10
–15

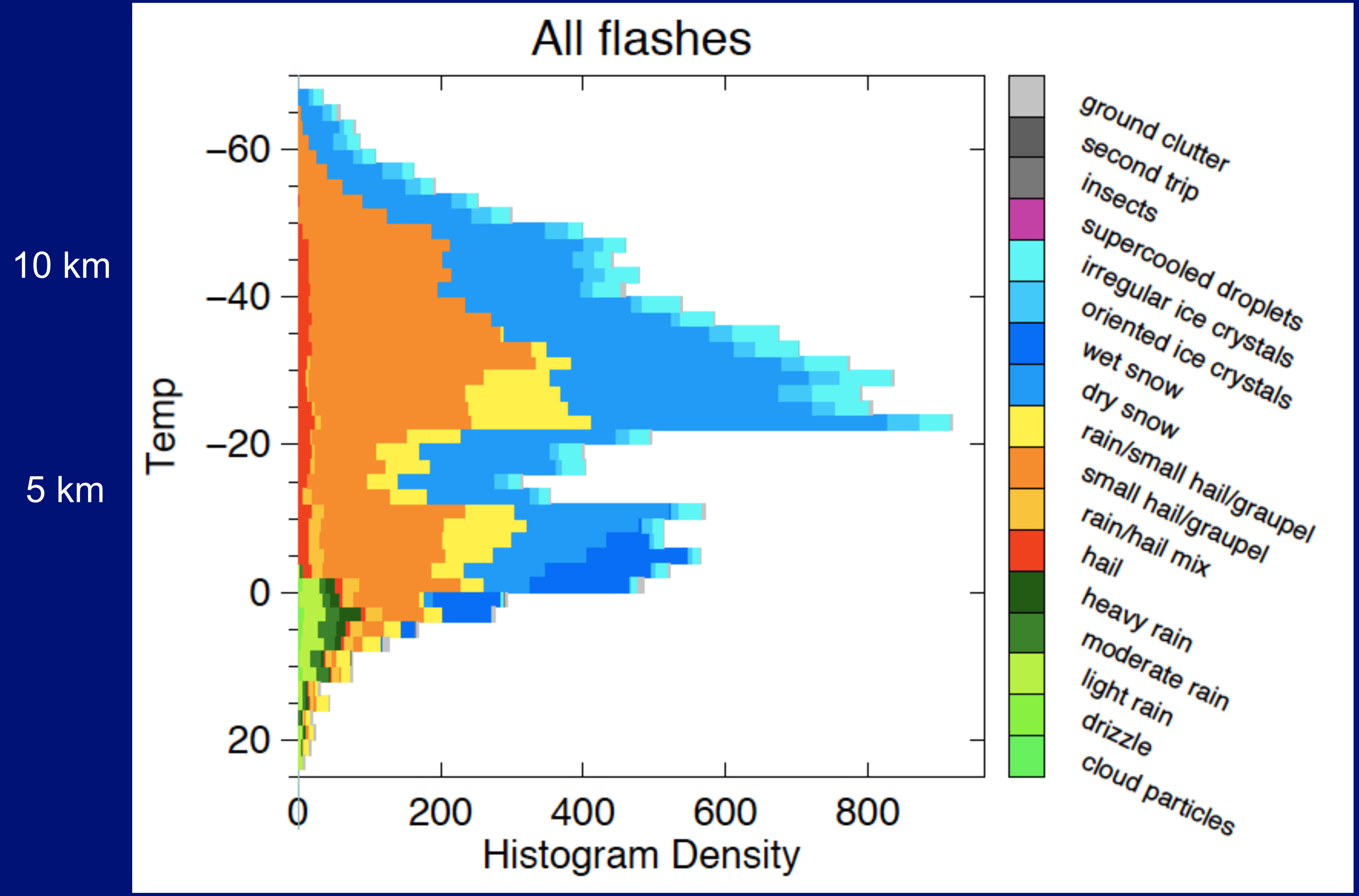


20060623T170136
Altitude (km)
15
10
5
0
0
10
20
30
40
Dist along slice (Origin = –45.00, 16.00)
60
55
50
45
40
35
30
25
20
15
10
5
0
–5
–10
–15


20060623T170136
Altitude (km)
Dist along slice (Origin = –45.00, 16.00)
0
5
10
15
0
10
20
30
40
ground clutter
second trip
insects
wet snow
dry snow
rain/hail mix
hail
heavy rain
moderate rain
light rain
drizzle
cloud particles



All flashes
16465 flashes with PD
Relative Frequency
0.30
0.20
0.10
0.00
cloud particles
drizzle
light rain
moderate rain
heavy rain
hail
rain/hail mix
small hail/graupel
rain/small hail/graupel
dry snow
wet snow
oriented ice crystals
irregular ice crystals
supercooled droplets
insects
second trip
ground clutter


All flashes
10 km
5 km
Temp
−60
−40
−20
0
20
0
200
400
600
800
Histogram Density
ground clutter
second trip
insects
supercooled droplets
irregular ice crystals
oriented ice crystals
wet snow
dry snow
rain/small hail/graupel
small hail/graupel
rain/hail mix
hail
heavy rain
moderate rain
light rain
drizzle
cloud particles