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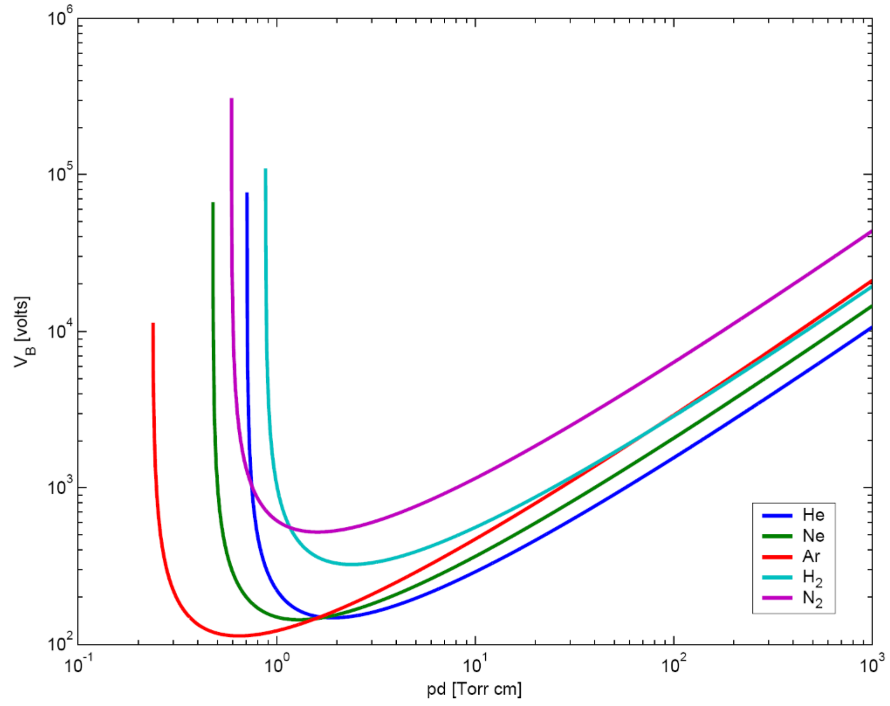
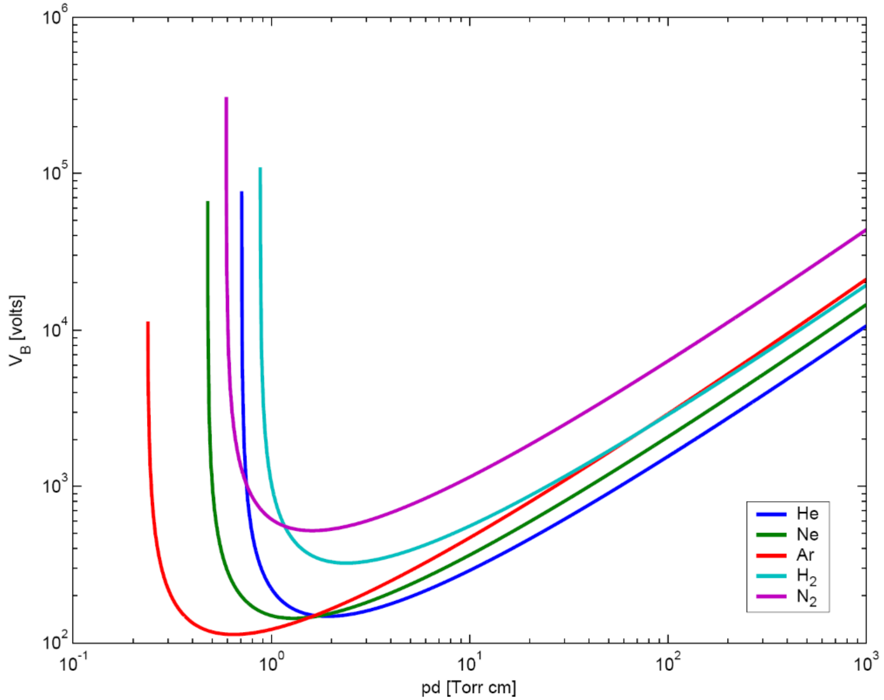


Maximum electric fields

- Breakdown field at sea level: E_{break} = 30 kV/cm
- At 6 km: E_{break} = 16 kV/cm → Paschen law

- But also presence of water drops decreases breakdown field:
  1.4 mm diameter water drops leads to
  E_{break} = 10 kV/cm



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- Breakdown field at sea level: E_{break} = 30 kV/cm
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Table 3.2. *Maximum electric field magnitudes measured in thunderclouds*

Reference	Sounding type	Maximum electric field, V m^{-1}
Gunn (1948)	Aircraft	3.4×10^5
Imyanitov *et al.* (1971)	Aircraft	2.8×10^5
Winn *et al.* (1974)	Rockets	4×10^5
Winn *et al.* (1981)	Balloons	1.4×10^5
Weber *et al.* (1982)	Balloons	1.1×10^5
Byrne *et al.* (1983)	Balloons	1.3×10^5
Fitzgerald (1984)	Aircraft	1.2×10^5
Marshall and Rust (1991)	Balloons	1.5×10^5
Kasemir (as reported by MacGorman and Rust 1998)	Aircraft	3×10^5

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Winn *et al.* (1974)	Rockets	4
Winn *et al.* (1981)	Balloons	1.4
Weber *et al.* (1982)	Balloons	1.1
Byrne *et al.* (1983)	Balloons	1.3
Fitzgerald (1984)	Aircraft	1.2
Marshall and Rust (1991)	Balloons	1.5
Kasemir (as reported by MacGorman and Rust 1998)	Aircraft	3

kV/cm

Maximum electric fields

- Breakdown field at sea level: E_{break} = 30 kV/cm
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- **BUT**: maybe some very strong field locally and short live

- We might hear more about that in later talks about runaway electrons

Charge densities

- $0.9 \cdot 5 \cdot 10^5\ \mathrm{C}/$

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- $0.9 \cdot 5 \cdot 10^5\ \mathrm{C} / \left(\frac{4}{3} \pi \left(\left[R_{\mathrm{Earth}} + 5\ \mathrm{km} \right]^3 - \ {R_{\mathrm{Earth}}}^3 \right) \right)$

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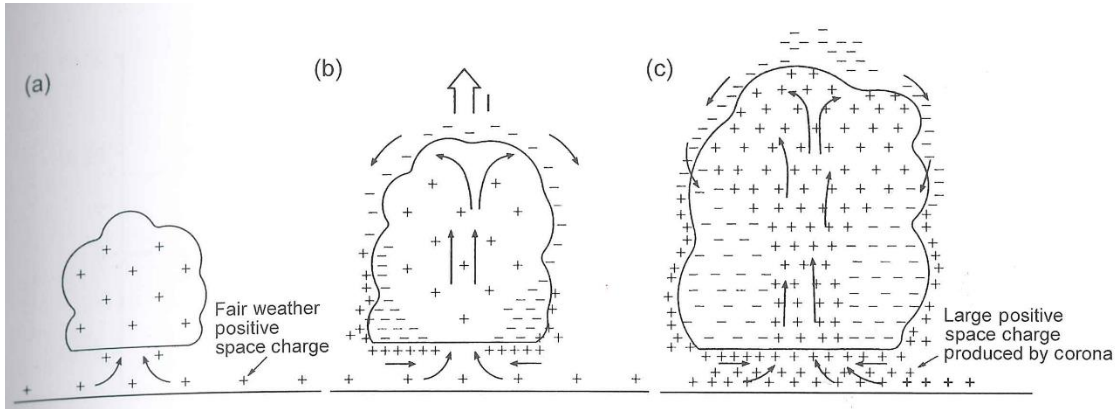
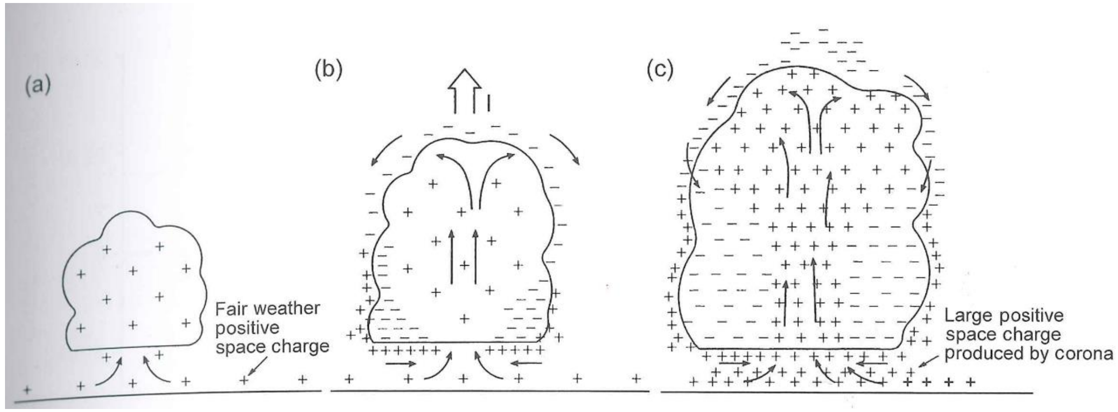
- $\sim\ 0.3\ \ - 3\ \mathrm{nC/m^3}$. Locally can go up to $100\ \mathrm{nC/m^3}$

Cloud electrification mechanism: Convection

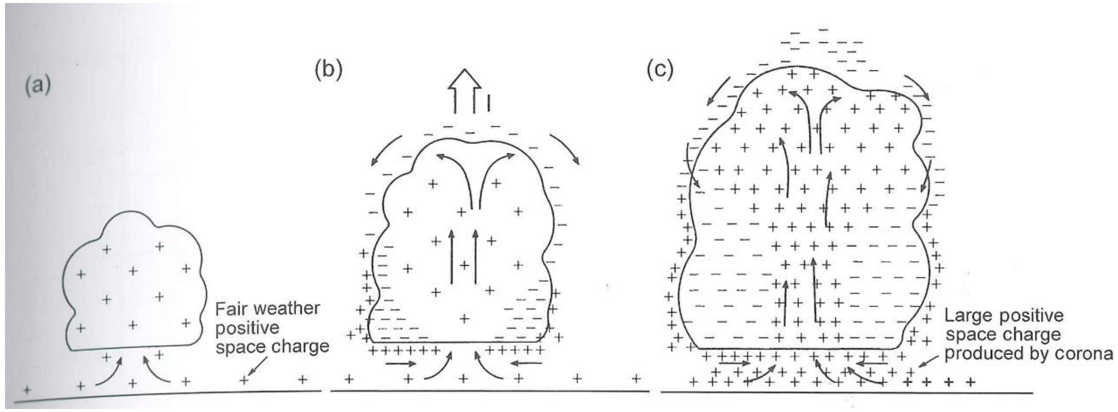


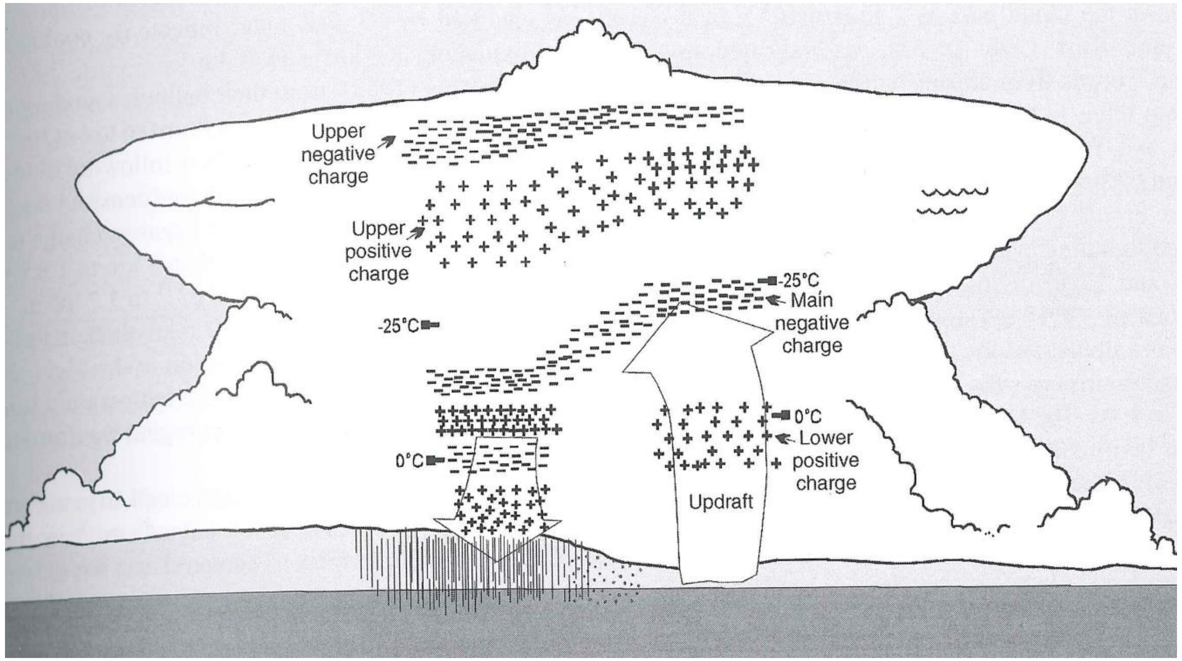
Cloud electrification mechanism: Convection



Remember: Fair-weather space charge: $\sim\ 0.2\ \mathrm{pC/m^3}$

Cloud electrification mechanism: Convection





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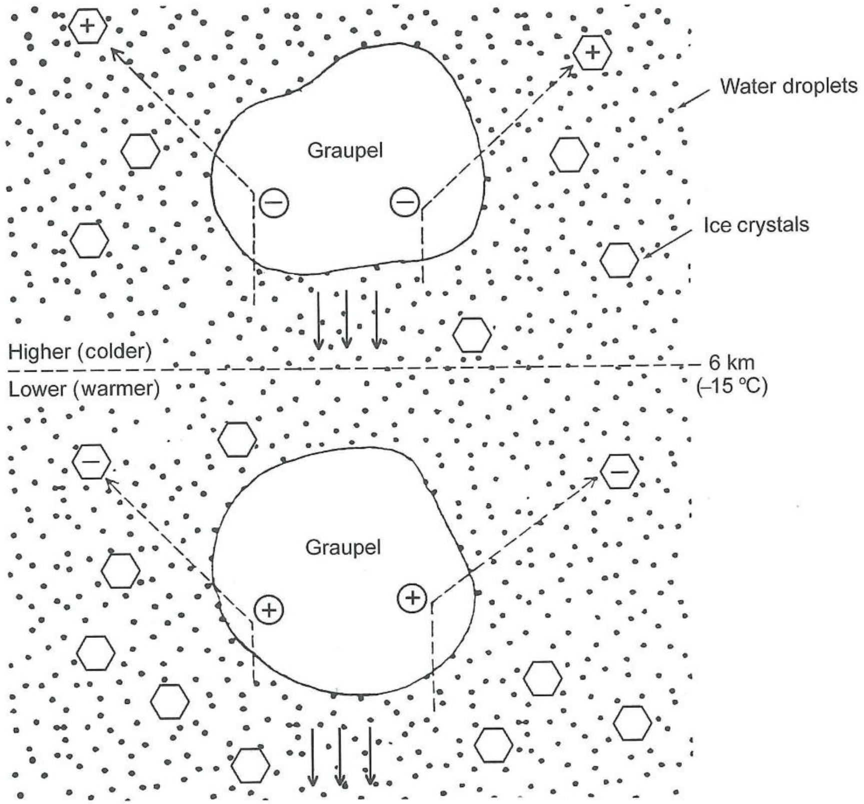
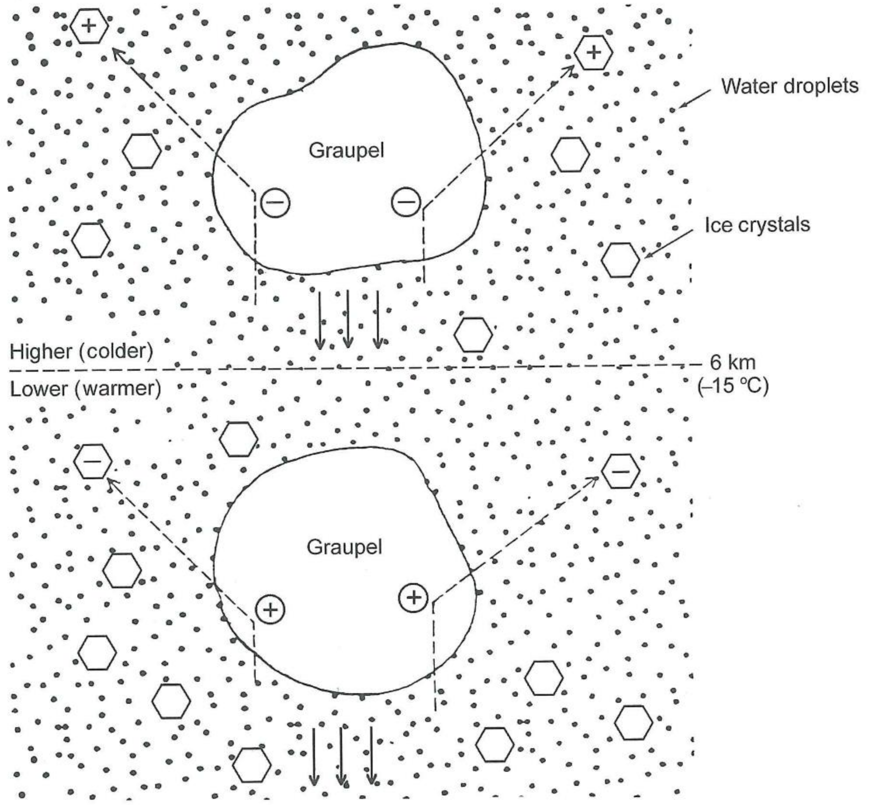
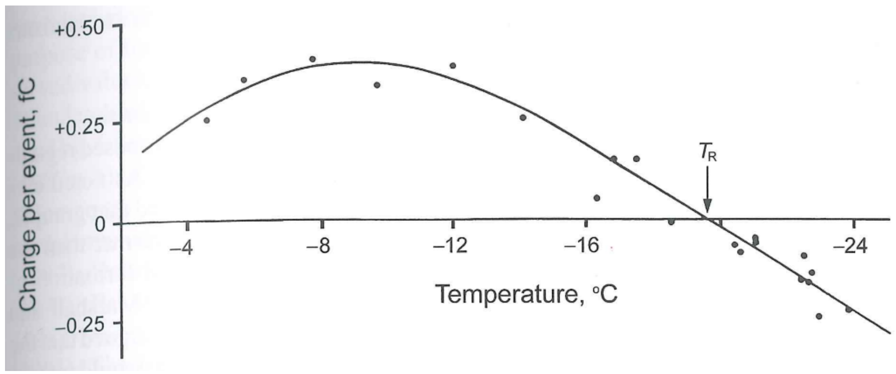
Cloud electrification mechanism: Graupel-ice



Cloud electrification mechanism: Graupel-ice





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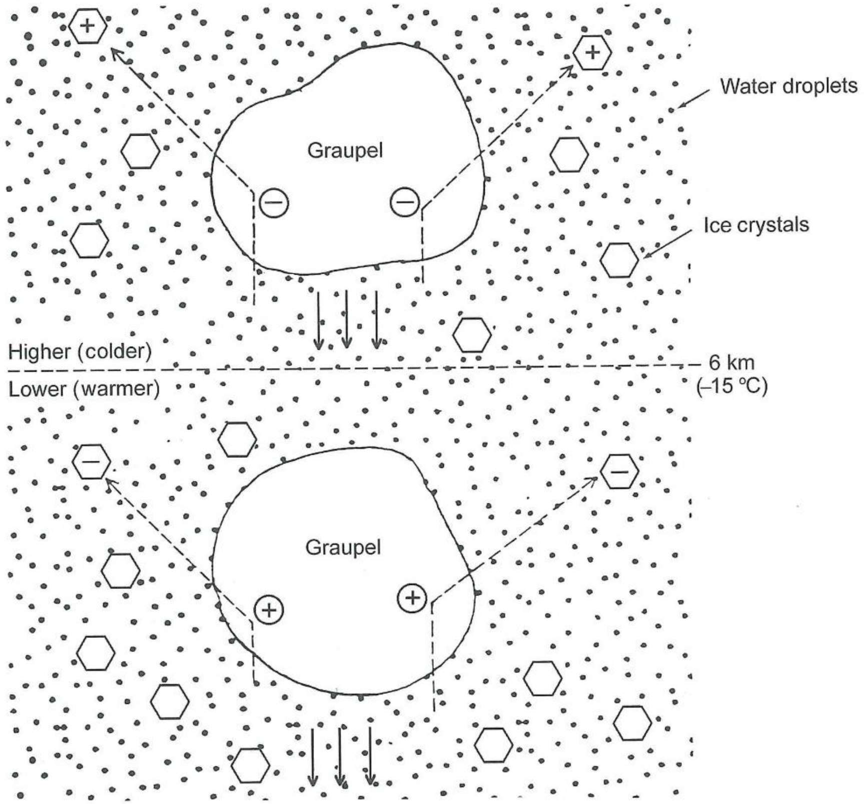
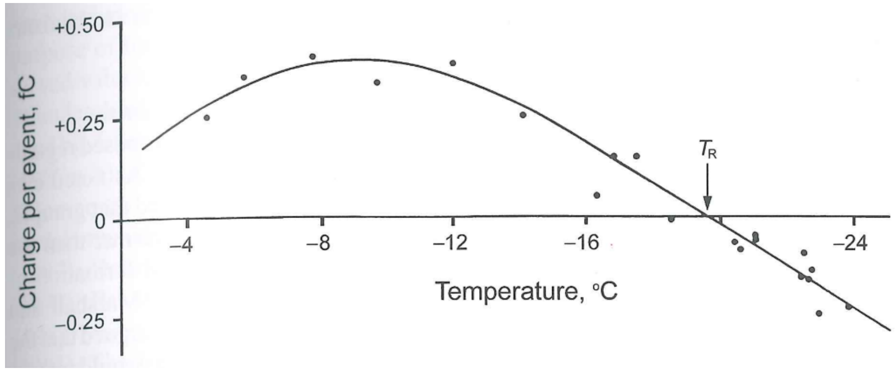


0.25 fC ≃ 1560 e



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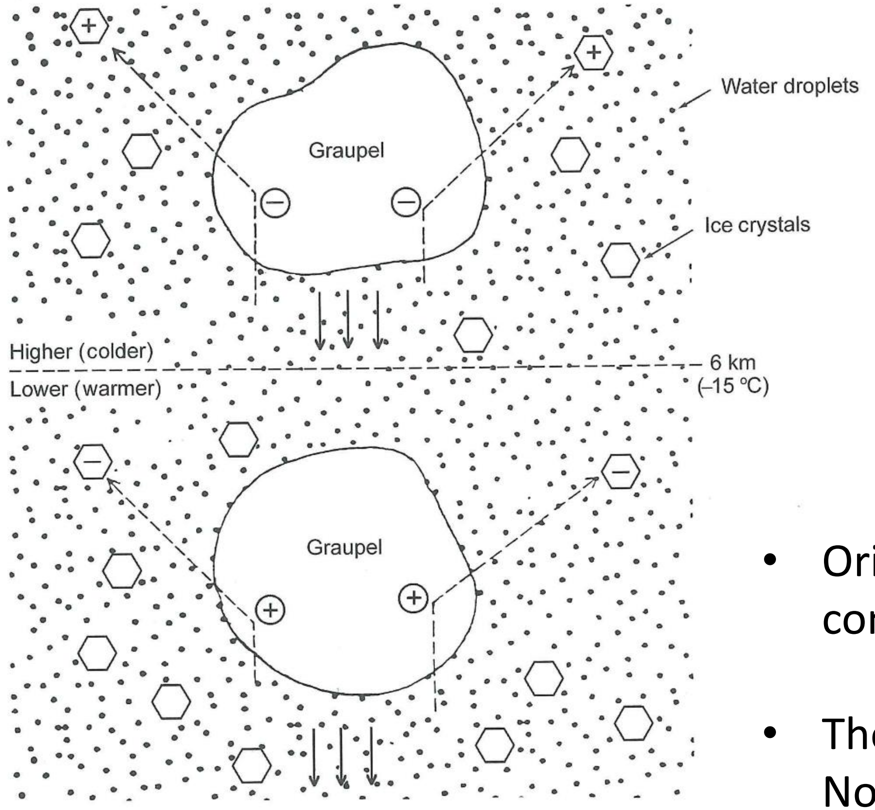

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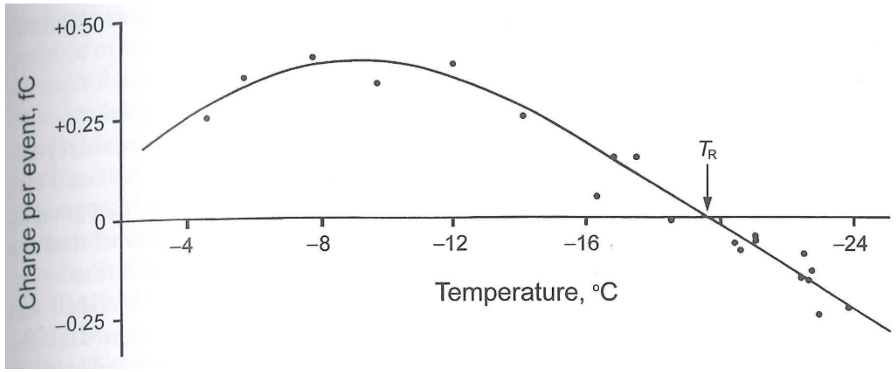

- Origin of sign depends on many factors (temperature, cloud water content, ice criystal size, relative velocity, ….).

- Thought to be correlated to ice and graupel surface growth
  No consensus on physical details.

- Still this is the priviledged theory since

  Charge density of precipitation ~ charge density inferred from E-field

Lightning representation in numerical cloud models

- Most model make crude assumptions but still show some reasonable values for charge per unit lightning length, total charge transfer and dipole moment charge.

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  - Lightning staring always at same grid point with max E field value
  - Graupel-ice mechanism as electrification
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  - Lightning staring always at same grid point with max E field value
  - Graupel-ice mechanism as electrification
  - …

  - Even refined versions still lack fundamental limits: eg. Lightning initiation criterion still remains an open question.

Non-cumulonimbus

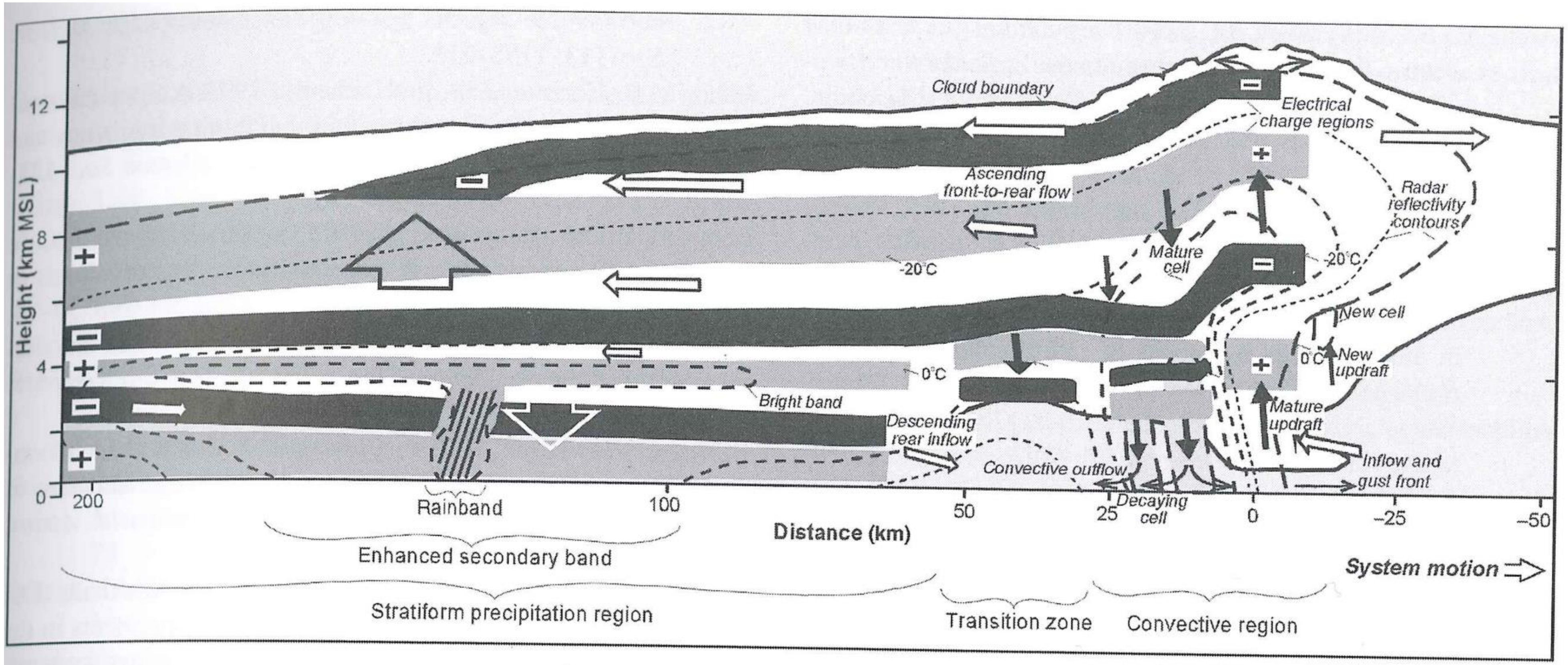
Table 3.3. *Median and maximum measured values of* $|E_z|$ *in various types of stratiform clouds. Adapted from Imyanitov* et al. *(1971)*

	Median value of $|E_z|$, V m^{-1}			
Type of cloud	St Petersburg, Russia (60° N)	Kiev, Ukraine (50° N)	Tashkent, Uzbekistan (41° N)	Maximum measured value of $|E_z|$, V m^{-1}
Stratus (St)	100	120	130	$(2–3) \times 10^3$
Stratocumulus (Sc)	80	100	100	$(2–3) \times 10^3$
Altocumulus (Ac)	40	80	70	5×10^3
Altostratus (As)	100	150	350	2×10^4
Nimbostratus (Ns)	150	250	500	4×10^4

Table 3.4. *Average thickness (m) of various types of stratiform cloud. Adapted from Imyanitov* et al. *(1971)*

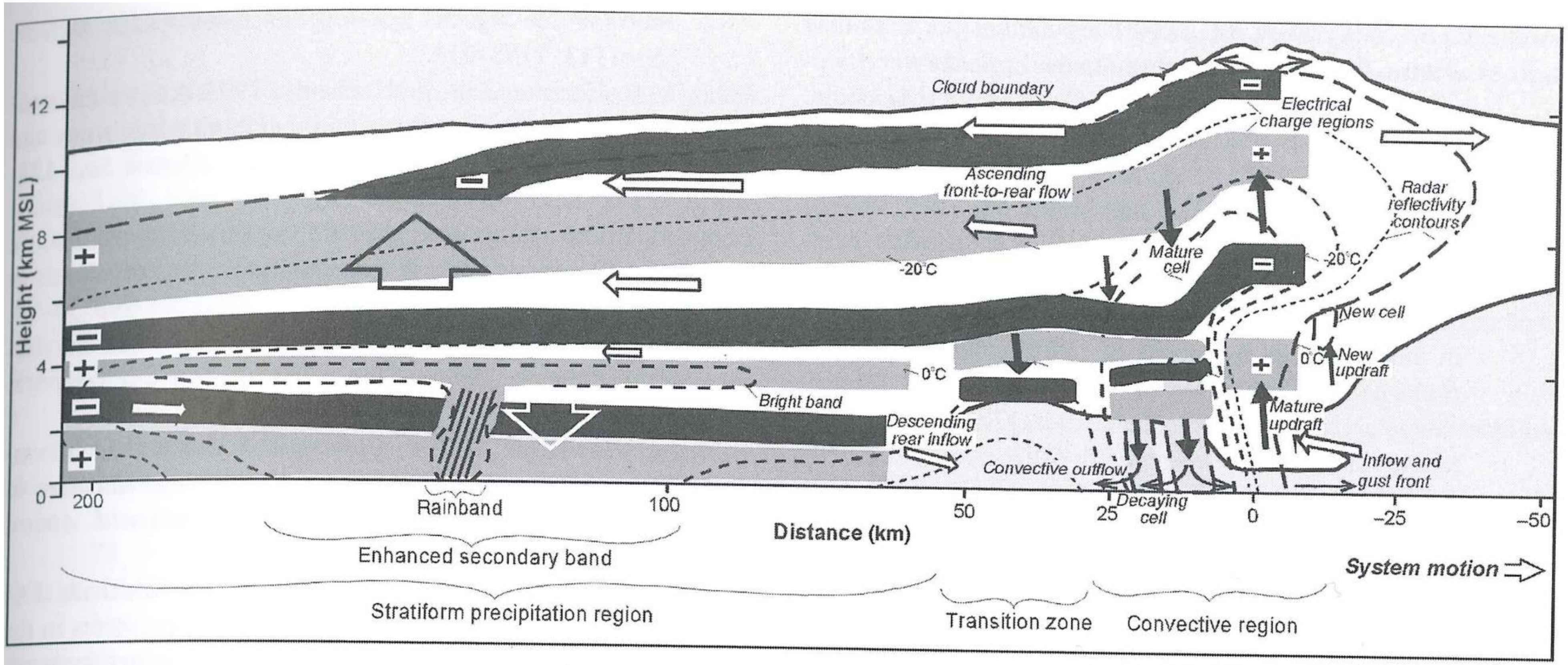
	Single charge layer		Two charge layers		
Type of cloud	+	−	±	∓	Multiple charge layers
St	200	200	450	450	700
Sc	260	250	400	450	700
As	650	700	800	900	1500
Ns	650	700	950	1600	2000

Non-cumulonimbus



Non-cumulonimbus

+ 32 MV



Non-cumulonimbus

$0.2\ \mathrm{nC/m^3}$

$-\ 2.5\ \mathrm{nC/m^3}$

$3.0\ \mathrm{nC/m^3}$

$-0.5\ \mathrm{nC/m^3}$