Solar wind - atmospheric electricity - cloud microphysics connections to weather

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UTD

Outline

- Aerosols, droplets, global electric circuit & particle charging
- Elements of a mechanism
- Model effect of charge on scavenging rates of aerosols by H_2O droplets
- Amplification effects
- Observations - placed in the conceptual framework
- Conclusions/Overview

Aerosols are cloud condensation nuclei

- Fine solid particle or liquid droplet:
  - natural: fog, forest exudates, geyser steam
  - artificial: dust, particulate air pollutants, smoke

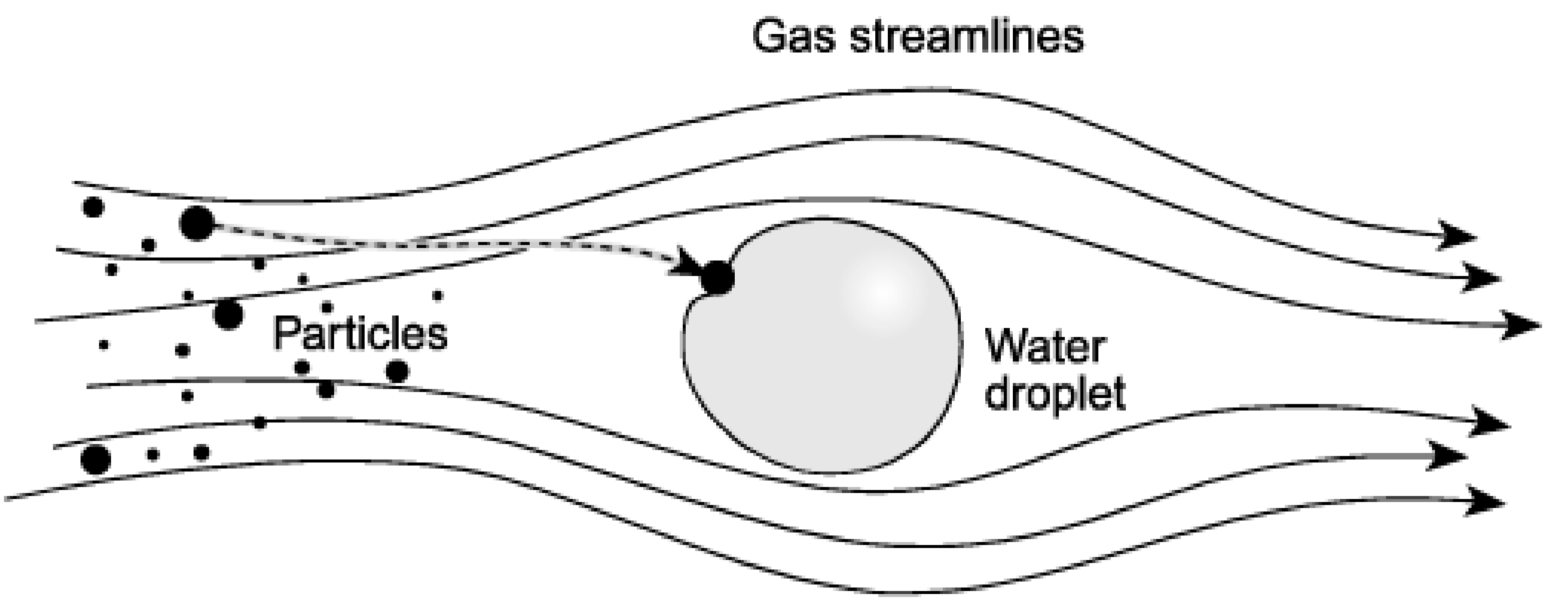
- Key in cloud physics, act as:
  - cloud condensation nuclei (CCN)
  - ice-forming nuclei (IFN)

- Changes in concentrations and size distributions of CCN and IFN affect droplet size distributions and precipitation

- In turn, affects cloud cover and storm invigoration – amplification

Loss of aerosols

Aerosols removed by:
- dry deposition (collision with solids)
- wet deposition (collision with water droplets/snow etc),
  e.g. ‘below-cloud scavenging’ of aerosols by precipitation
  e.g. ‘in-cloud scavenging’ by collision with H_2O



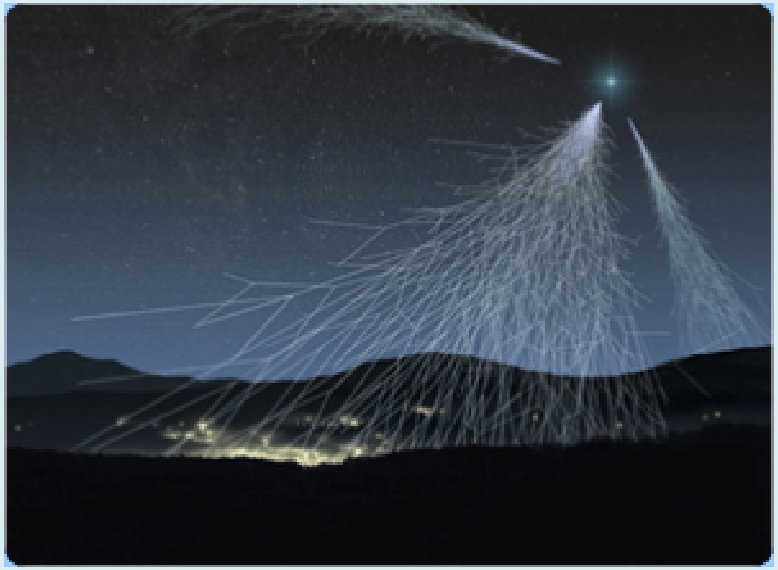
Impaction: particle not able to follow streamlines round obstacle due to inertia

Scavenging of aerosol particles by water droplets

- Base level (no charge effects) dominated by:

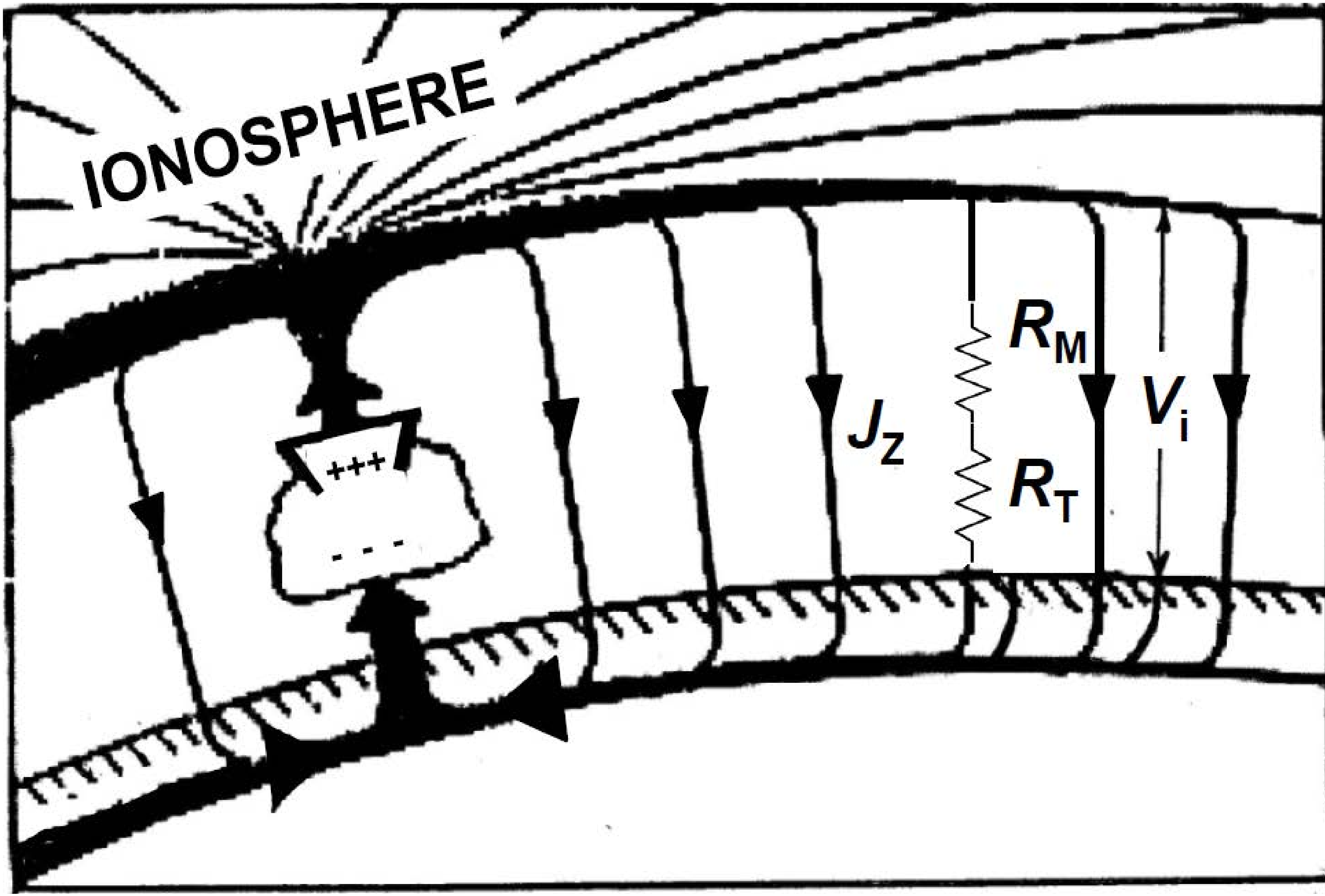
  - small particles (diffusion)
  - large particles (intercept, weight and flow effects)

- However, aerosols *can* be charged. Ions produced by GCR attach to aerosol particles



- Aerosols at equilibrium:
  - positives : neutrals ~ 1: 3
  - negatives : neutrals ~ 1: 2

Global atmospheric electric circuit



Global atmospheric electric circuit

- Each of ~1000 highly electrified storms sends ~ 1 A to ionosphere
- Charges it to V_i ~ 250 kV, varying diurnally and from day-to-day

- Local downward current density J_z is given by Ohm's Law in 3D:

$$J_z = V_i / (R_M + R_T)$$

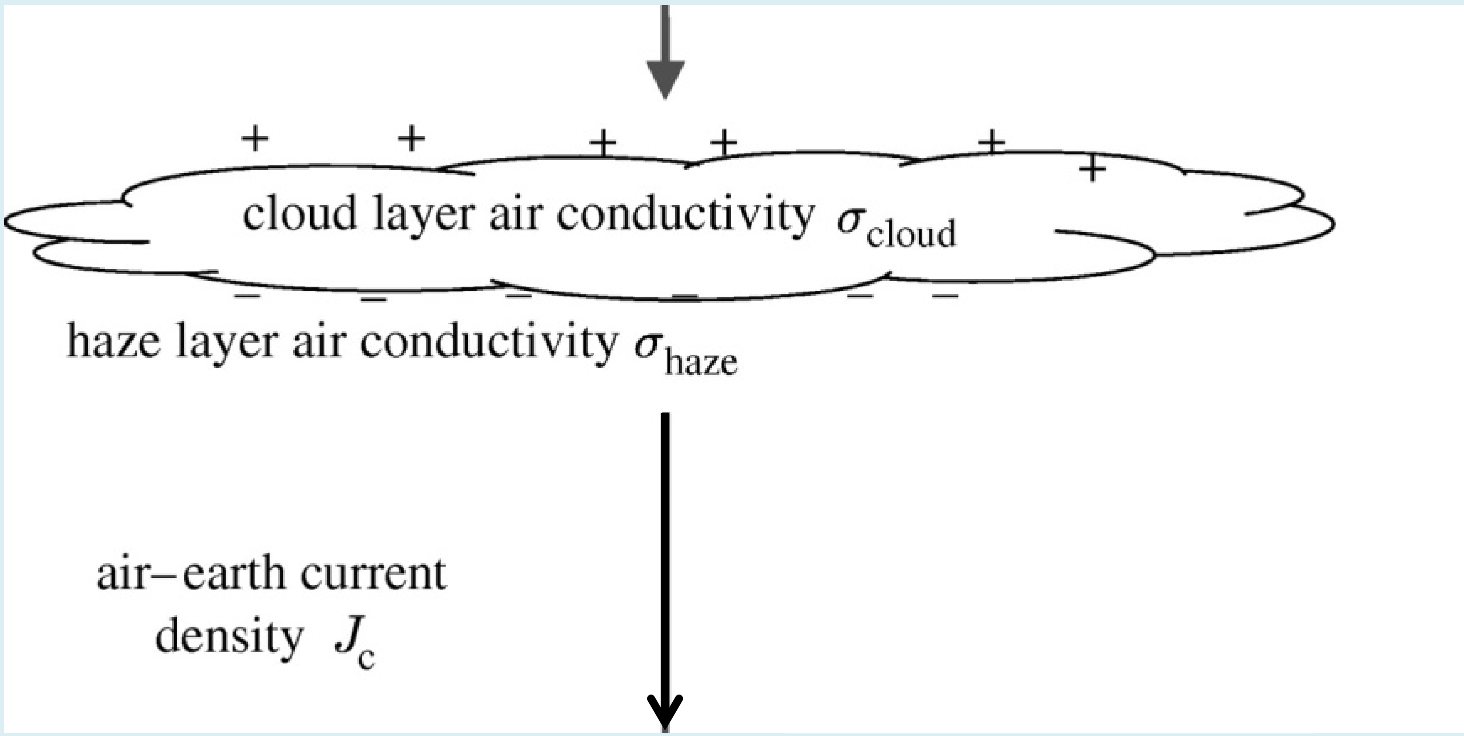
R_M column resistance (Ω-m^2) of middle atmosphere
R_T ….. troposphere

- Any change in V_i, R_M, or R_T affects J_z, e.g.:

Polar V_i varies with solar wind speed and magnetic field

J_z effect on cloud processes?

- J_z generates space charge (Poisson's equation) as it flows through gradients in conductivity

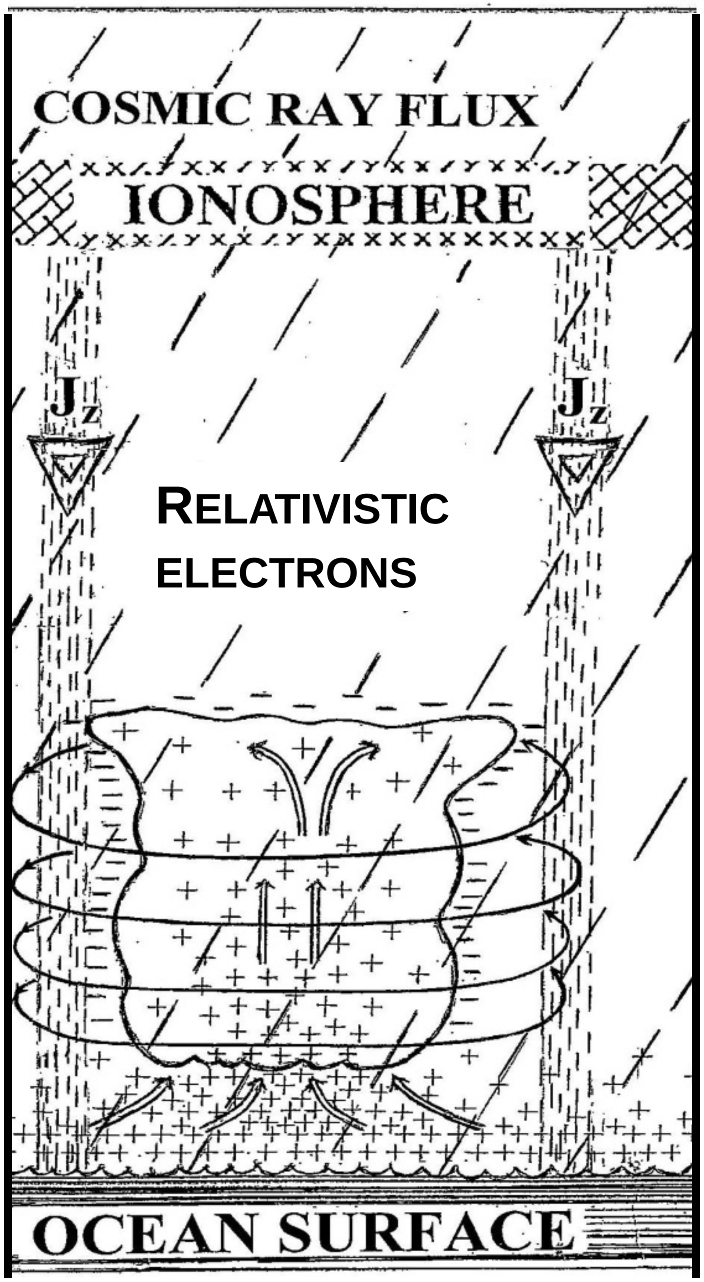


- Space charge perturbs the *+ve: –ve* ratio for aerosols (and droplets)

- *If* charging of particles and droplets affects the numbers of CCN then ***solar-driven variations in J_z affect* cloud processes**

Updrafts

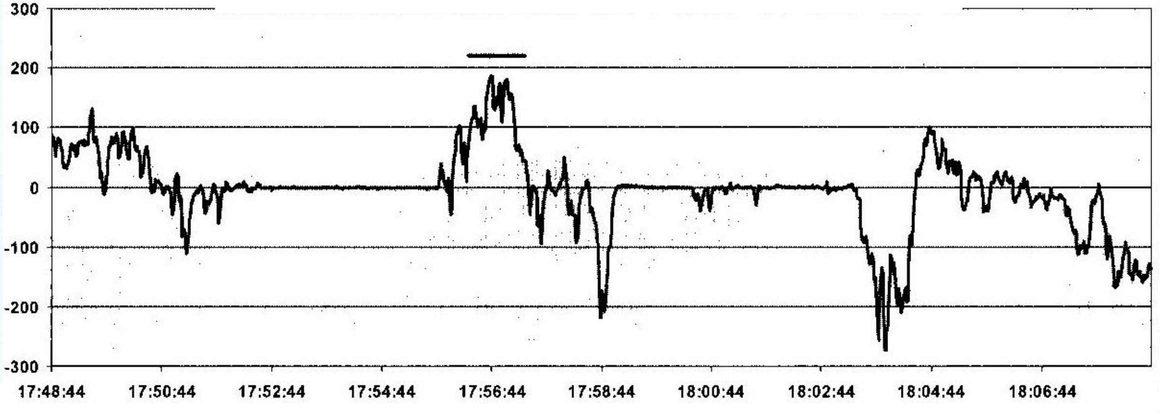
- Space charge attaches to aerosols in sea spray particles, haze, and fog near ocean surface
- Space charge convected into clouds by updrafts



Aircraft measurements of droplet charges

Counter flow virtual impactor mounted on plane wing

Electrometer current (fA) with time



Average droplet charge in layer cloud ~ 300e

- Regions with both + and - charged average droplet charges; average charges ranging from +300 e to -300 e
- Many measurements show comparable average charges on droplets
- Diffusion charging theory: charges on aerosols and droplets α radii
- Orders of magnitude greater in thunderstorms/deep convective clouds

Elements of a possible mechanism

- Galactic cosmic rays (GCR) ionise atmosphere
- Ions attach to aerosol particles ⇒ equilibrium *+ve: –ve ratio*
- Thunderstorms drive a global atmospheric electric circuit
- Downward current density $J_z = V_i /(R_M + R_T)$; V_i, R vary with solar inputs
- J_z flow leads to space charge at conductivity boundaries
- J_z - related space charge perturbs the *+ve: –ve* ratio
- Charge on aerosols particles (and on droplets) affects ‘scavenging rate’ of aerosols by droplets
- Therefore J_z can perturb cloud formation processes
- Amplification: via effects on albedo, IR opacity, cloud cover, balance in long/short-wave radiation; storm invigoration

Modelling scavenging rates of (aerosol) particles

- Trajectory simulations without diffusion

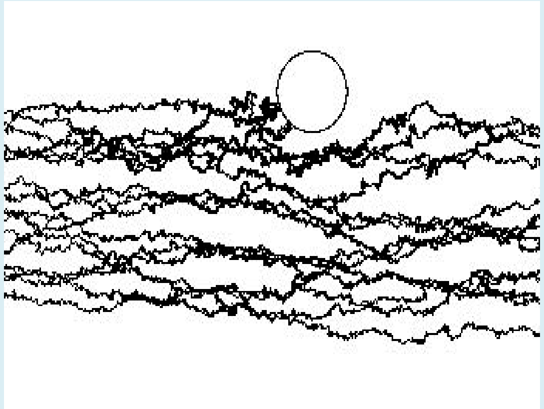
  [Tinsley et al. (2000, 2001), Tripathi & Harrison (2002), Tinsley et al. (2006), Tripathi et al. (2006), Zhou et al. (2009)]

- Trajectory simulations with diffusion [Tinsley 2012]

- Parameterizations of simulations
  - without diffusion [Tripathi et al. 2006]
  - with diffusion [Tinsley & Leddon 2013; **Zhou &Tinsley 2015]**

- Add realistic models of cloud charging,

  ⇒ scavenging rates in models of cloud formation/development



Modelling scavenging rates of (aerosol) particles

- Find collision efficiencies using trajectory simulations
- Convert to collision or scavenging rate coefficients, R ($m^3\ s^{-1}$)
- R multiplied by concentration of aerosol particles gives the rate of scavenging in numbers of particles scavenged per unit time
- Here, base level is set of results for zero charges $q = 0$, $Q = 0$
- Deviations:
  - *above is electro-scavenging*
  - *below is electro-antiscavenging*

Zhou and Tinsley (submitted 2015)

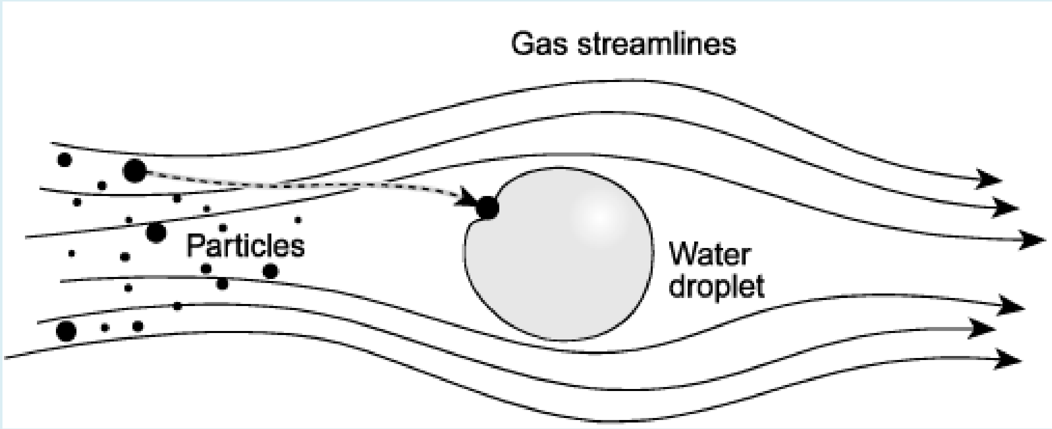
- *R* is a function of:
  - *Q*, droplet charge (0 – 200 e)
  - *q*, aerosol particle charge (0 - 50 e)

  - *A*, droplet radius (3 - 15 μm)
  - *a*, aerosol particle radius (0.004 – 2 μm)

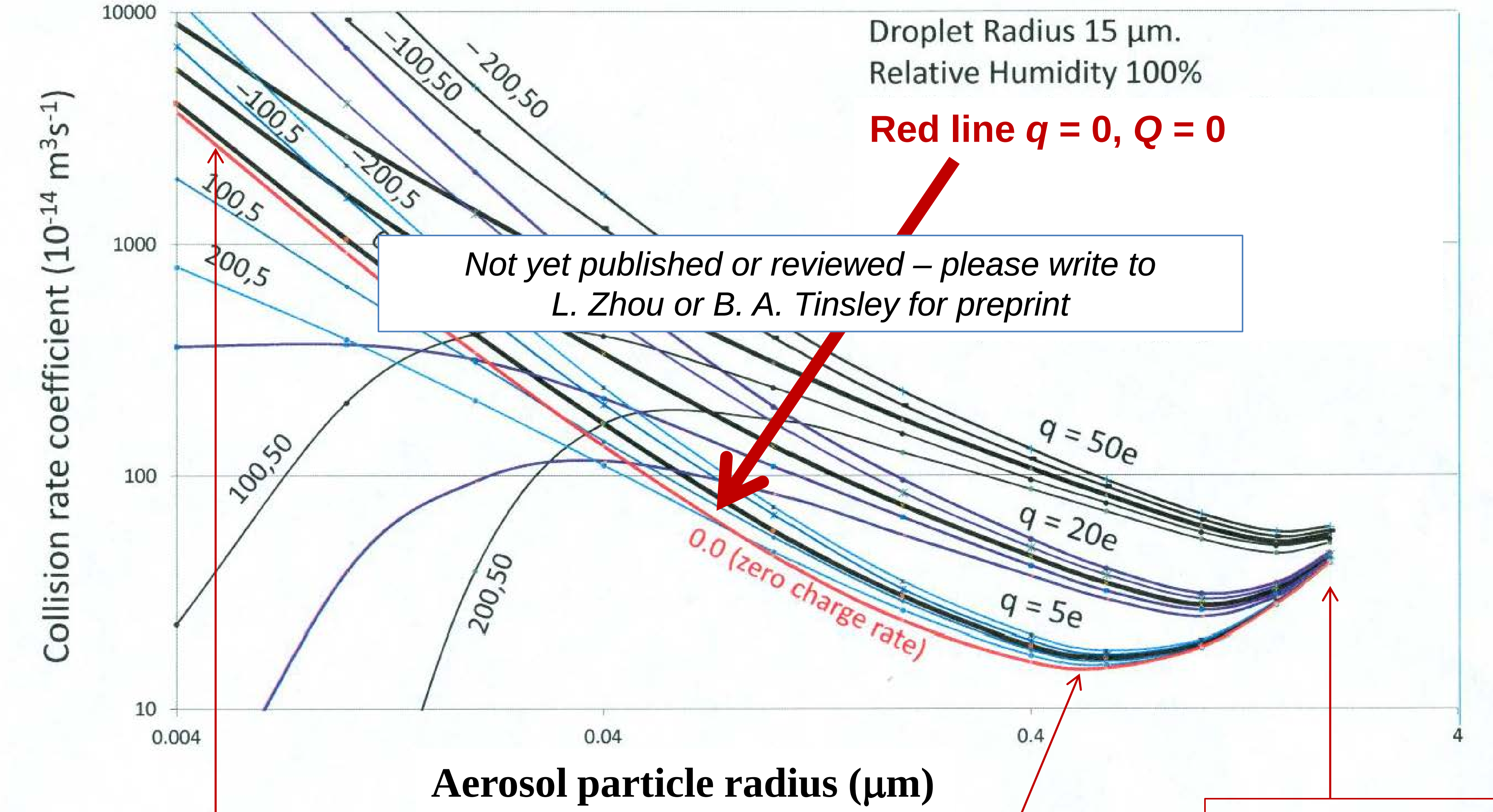
- Collisions of same and opposite sign modelled

  - Attractive or repulsive Coulomb inverse square law (large separations)
  - Attractive image charge forces (small separation)

- Diffusion
- Weight (Sedimentation)
- Flow around particle
- Inertia (Impaction)



Scavenging rate coefficients base line – no charge



Small particles: Diffusion

Rate of deposition lowest for particles of intermediate size

Large particles: Impaction/ Sedimentation/ Flow

Potential effect of J_z on clouds: uncharged droplets

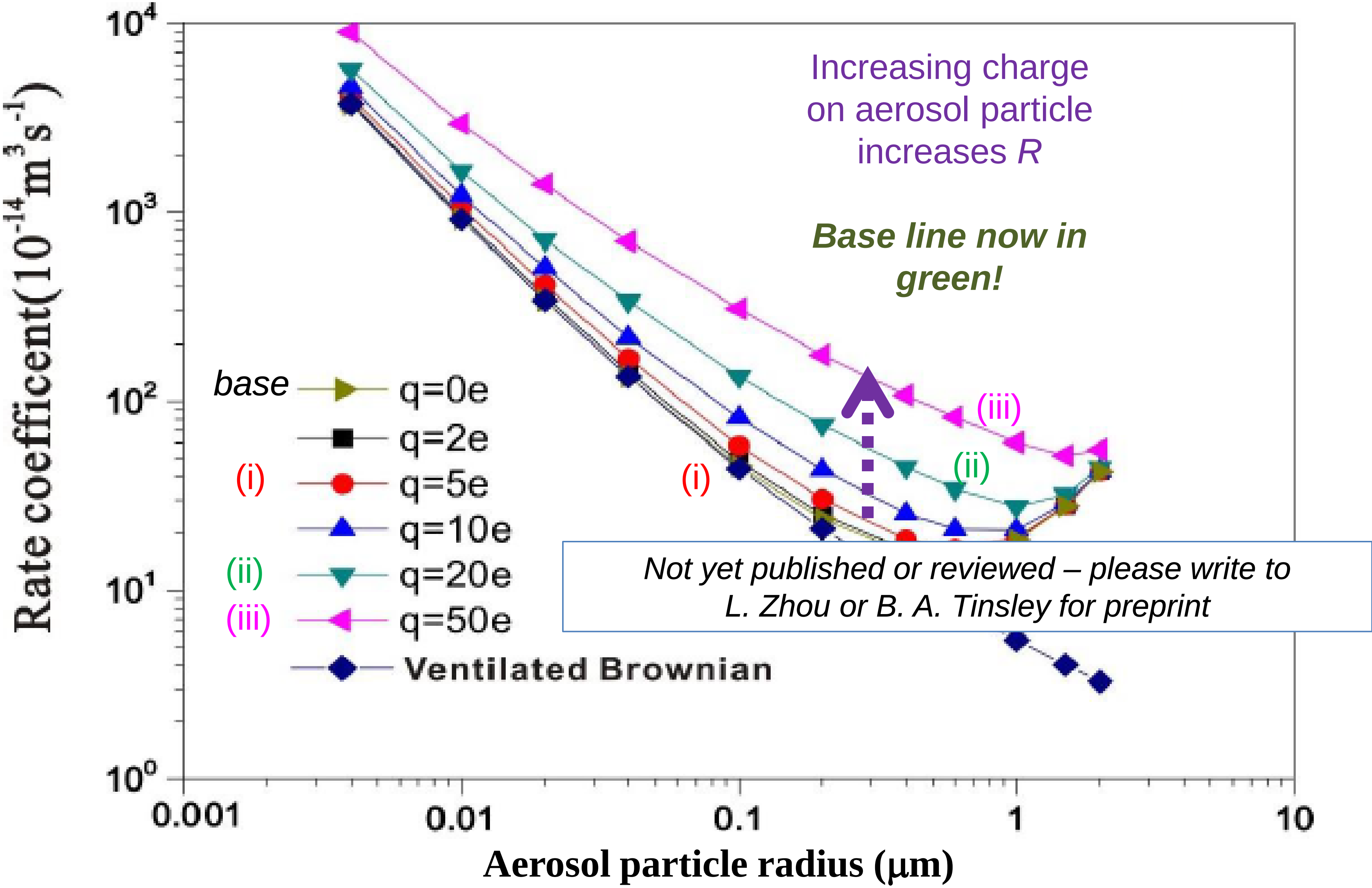
For an *uncharged* droplets:

increasing the charge on aerosol particles…

…always *increases scavenging rate* for particle radii ≤ 1 μm

due to the image force

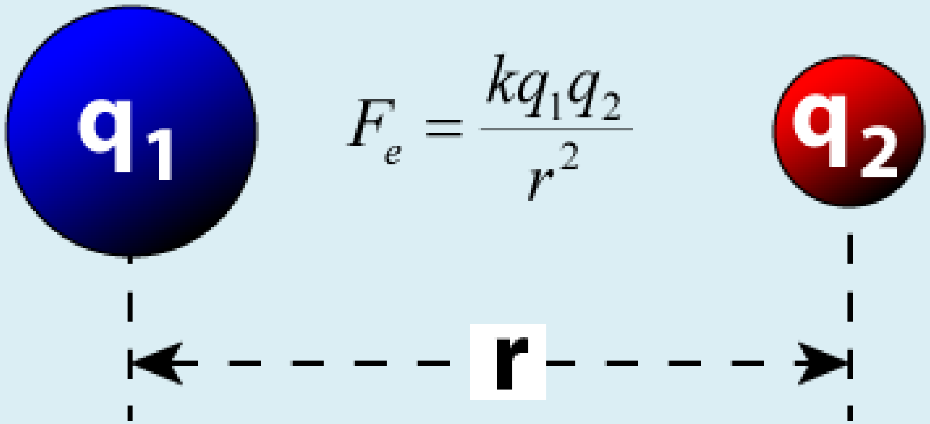
Scavenging rate coefficient: charged particles & uncharged droplets of radius 15 μm



Potential effect of J_z on clouds: charged droplets

For *charged* droplets:

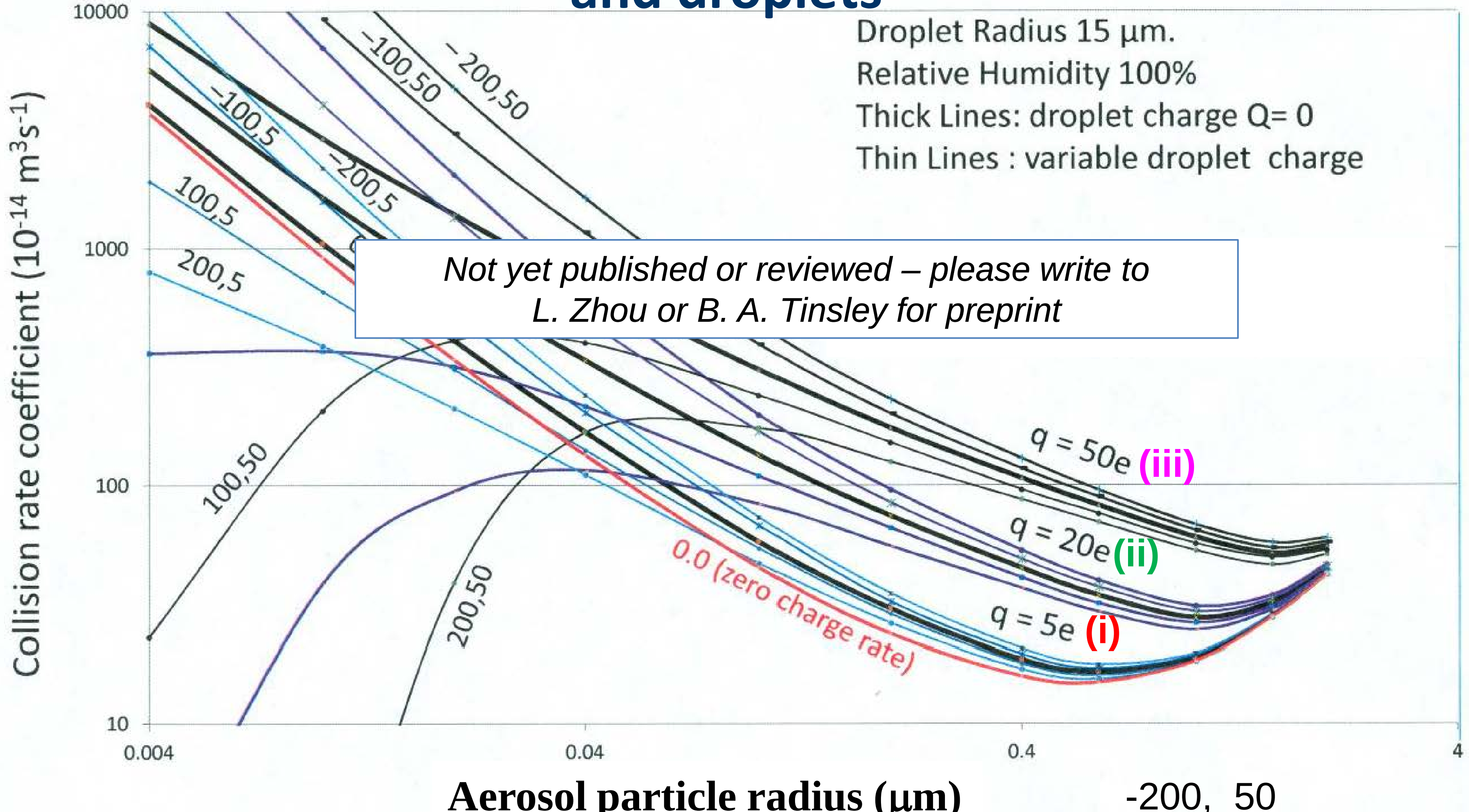
- can have *increase or decrease* in scavenging rate:



$$F_e = \frac{kq_1q_2}{r^2}$$

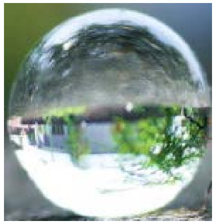
Results: thick curves are for no charge on droplets

Scavenging rate coefficients for charged aerosol particles and droplets



Not yet published or reviewed – please write to L. Zhou or B. A. Tinsley for preprint

-200, 50



Droplet charge

Particle charge

Potential effect of J_z on clouds: charged droplets

For *charged* droplets:

- can have *increase or decrease* in scavenging rate:

Thick curves are for no charge on droplets

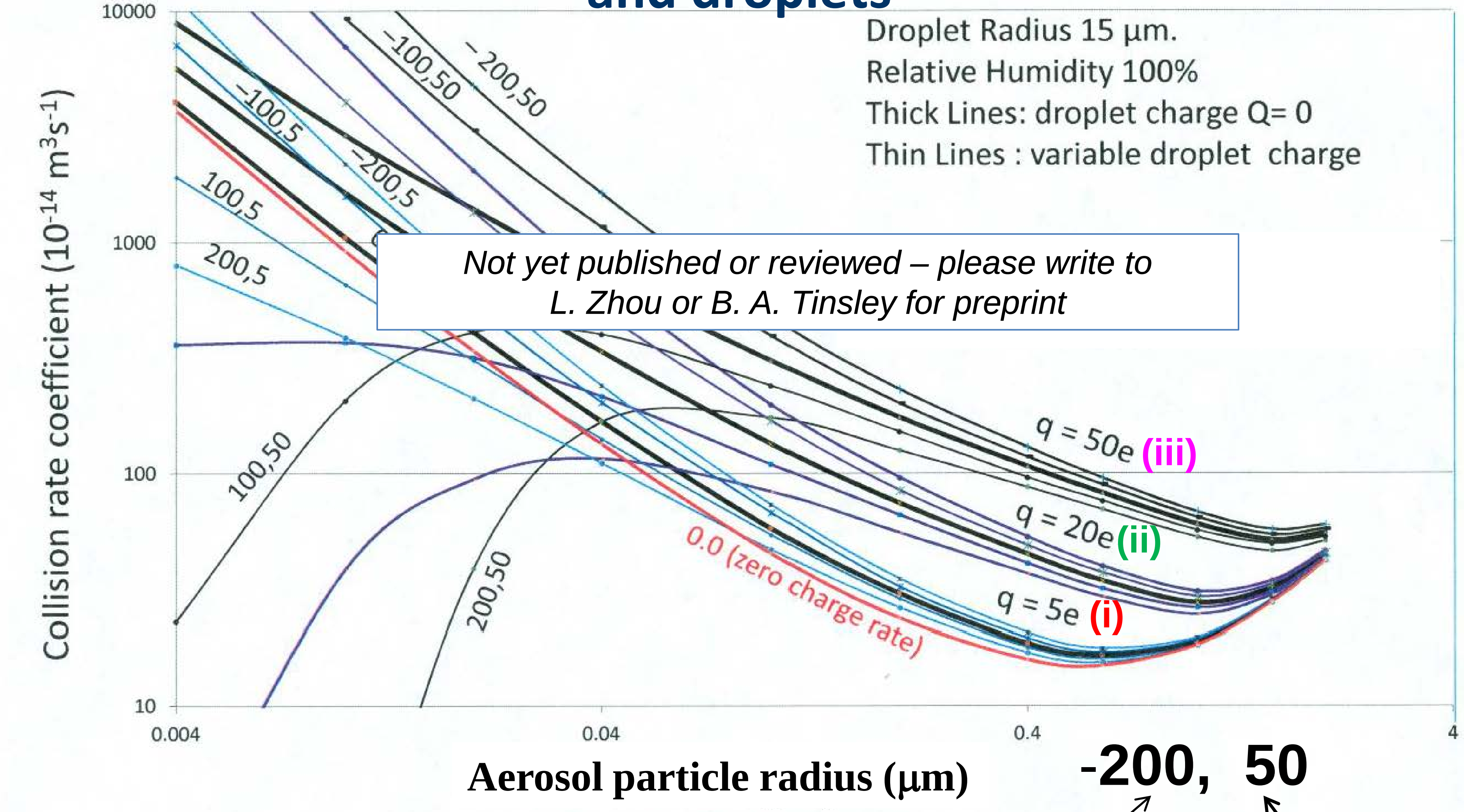
Thin curves are for different charges on droplets
e.g. -200, 50
droplet charge = -200 e; aerosol particle charge = +50 e

-200, 50 } rate increased over zero droplet charge case
-100, 50 } (Coulomb attraction)

0,50

} rate increased over base (image)

Scavenging rate coefficients for charged aerosol particles and droplets



Droplet charge

Particle charge

Scavenging effects: charged droplets

-200, 50
-100, 50

rate increased over zero droplet charge case (Coulomb attraction)

0,50

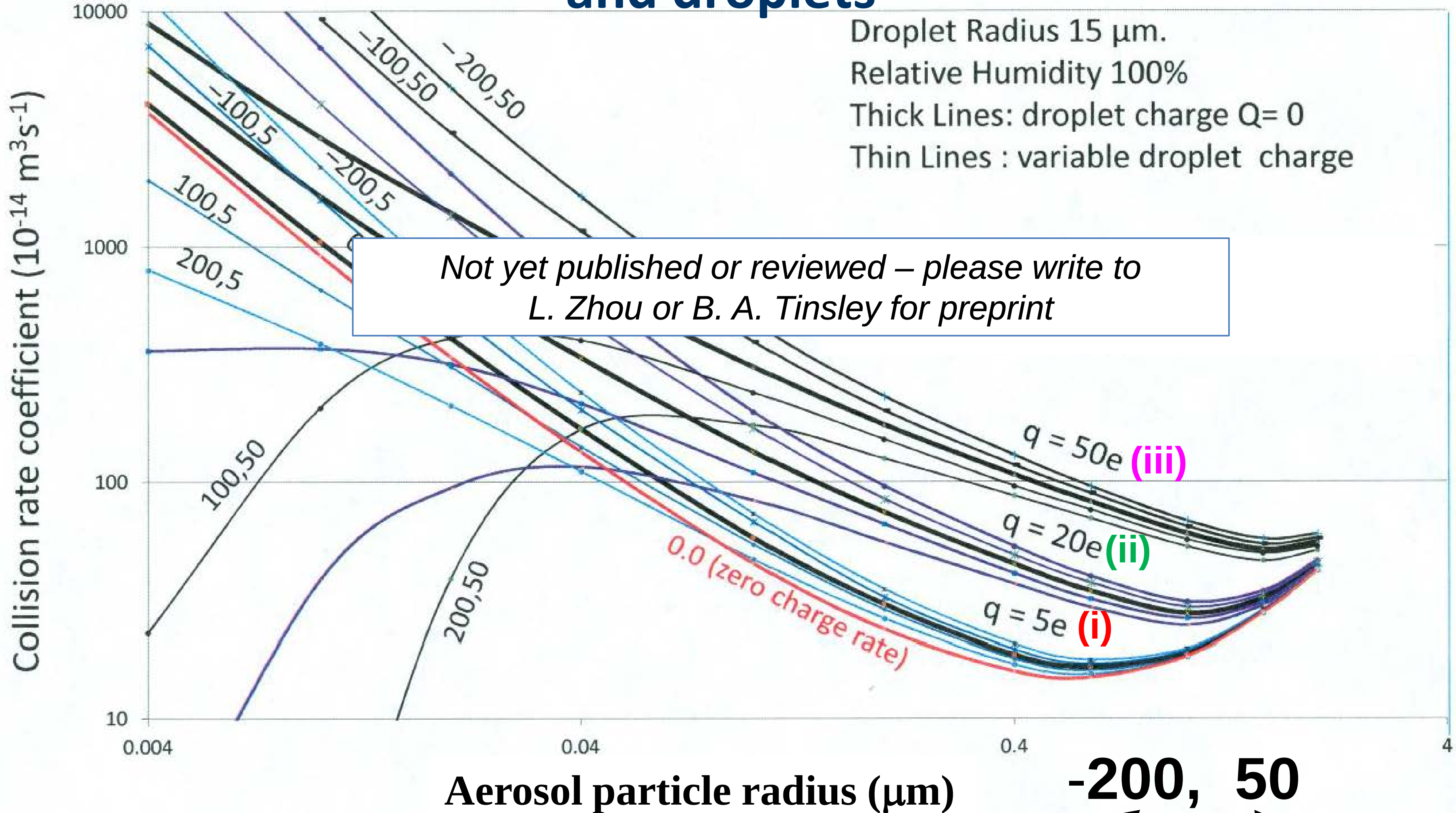
rate increased over base (image)

100, 50
200, 50

rate decreased over zero droplet charge case (Coulomb repulsion)

rate decreased over base for small particle radii

Scavenging rate coefficients for charged aerosol particles and droplets



-200, 50

Droplet charge

Particle charge

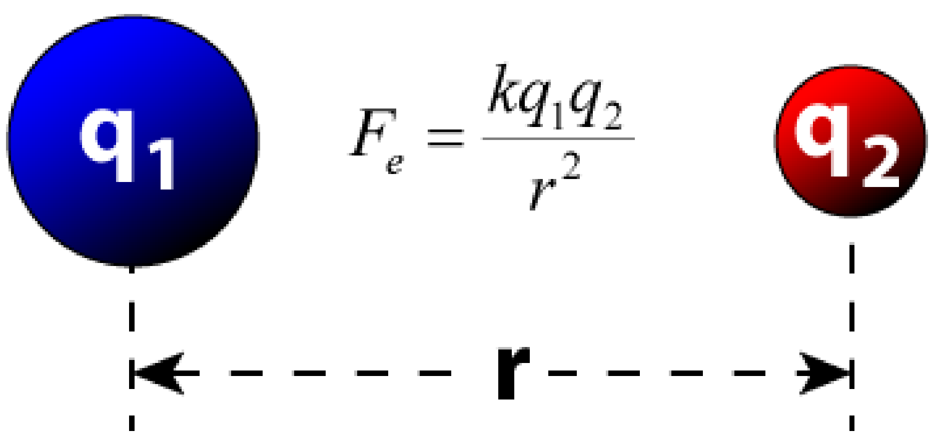
Demonstrated charge-related effect on scavenging rates

- Electric charge on particles and droplets affects **rates of collisions** (in-cloud scavenging)

- Charge can *increase or decrease scavenging rates*, depending on sizes, changing concentrations and size distributions

- Leads to size distribution changes in droplets, affecting coagulation and precipitation.

- Scavenging of ice-forming nuclei by supercooled droplets promotes contact ice nucleation, i.e., production of ice.



Need amplification of variations in input energy

ergs cm^{-2} sec^{-2} $\Rightarrow$ watts cm^{-2} sec^{-1}

1. INVIGORATION IN STORM CLOUDS

- Larger numbers of smaller CCN $\Rightarrow$ larger numbers smaller droplets

- Inhibits coagulation/precipitation, liquid water carried above freezing level, latent heat release, updraft invigoration

2. ALBEDO, COVER; IR OPACITY; RADIATION IN LAYER CLOUDS

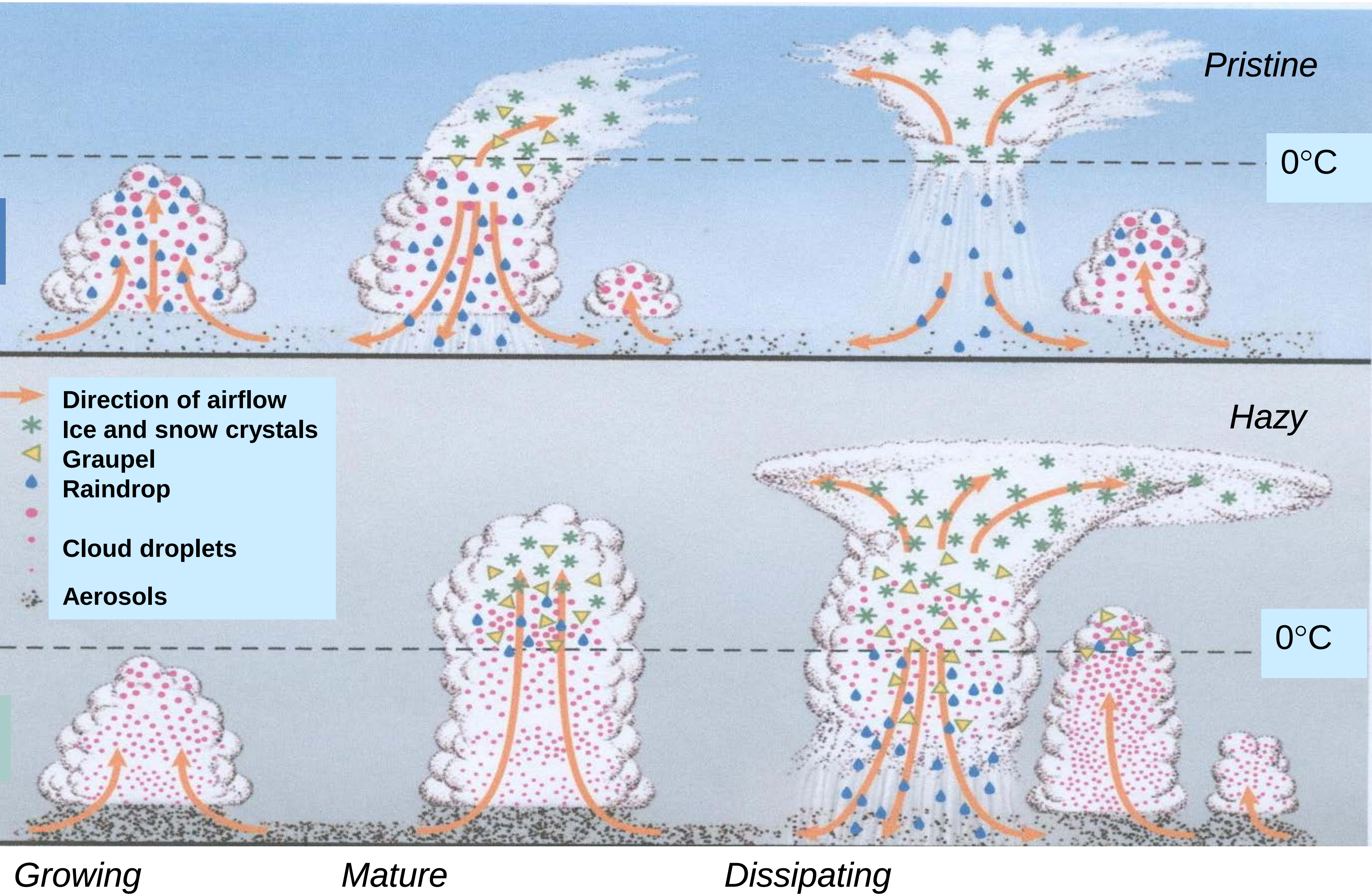
- Changes in CCN and IFN processes affect concentration/size distribution of droplets in layer clouds

- Directly affects albedo and infrared opacity.

- Indirectly affects cloud cover

- Changes balance in long/short-wave radiation

CCN concentration and storm invigoration



Rosenfeld et al. Science 2008

Timescales for atmospheric response: hours to days

- J_z responds to changes in V_i
  or column resistance < 10 mins

- J_z flows through clouds (cover 70% of globe)
  Takes few hours to few days
  for microphysics to respond to J_z

- Chemical and dynamical changes
  in stratosphere take
  weeks to months to propagate
  down to troposphere

Observed day-to-day atmospheric responses to J_z

A. Global ionospheric potential effect

e.g. Surface pressure variations driven by low-latitude thunderstorm and electrified shower generator

B. Polar cap ionospheric potential effect

e.g. tropospheric pressure variations driven by solar wind electric field

C. Relativistic electron flux effect

e.g. reduction in area of high vorticity of winter storms for HCS crossings

D. Solar energetic particle effects

Observed increase in tropospheric vorticity with SEP events

E. Cosmic ray effects

Changes in area of high tropospheric vorticity with GCR decreases

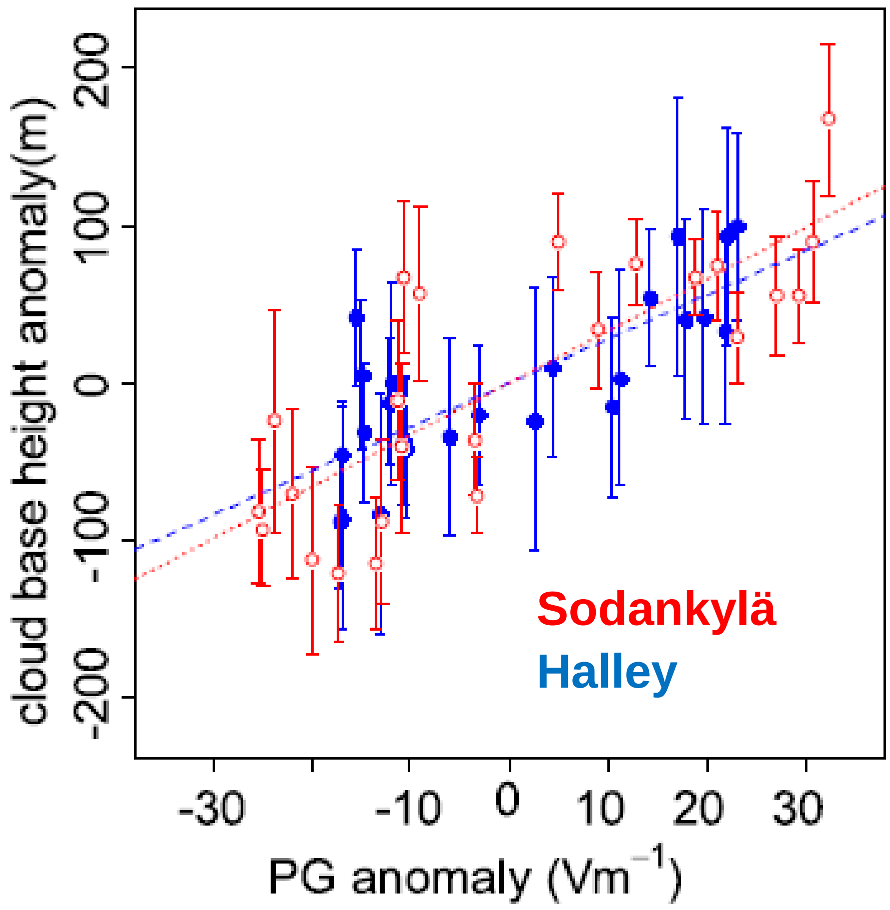
Changes in J_z : 10 – 20%

A. Global ionospheric electric potential effect

Harrison and Ambaum 2013

Lidar signal's reflection height from 'base' of layer clouds correlates with diurnal cycle in surface vertical electric field (right)

Hebert et al. 2012
500 hPa VAI correlates with low-latitude J_z variations
(not shown)

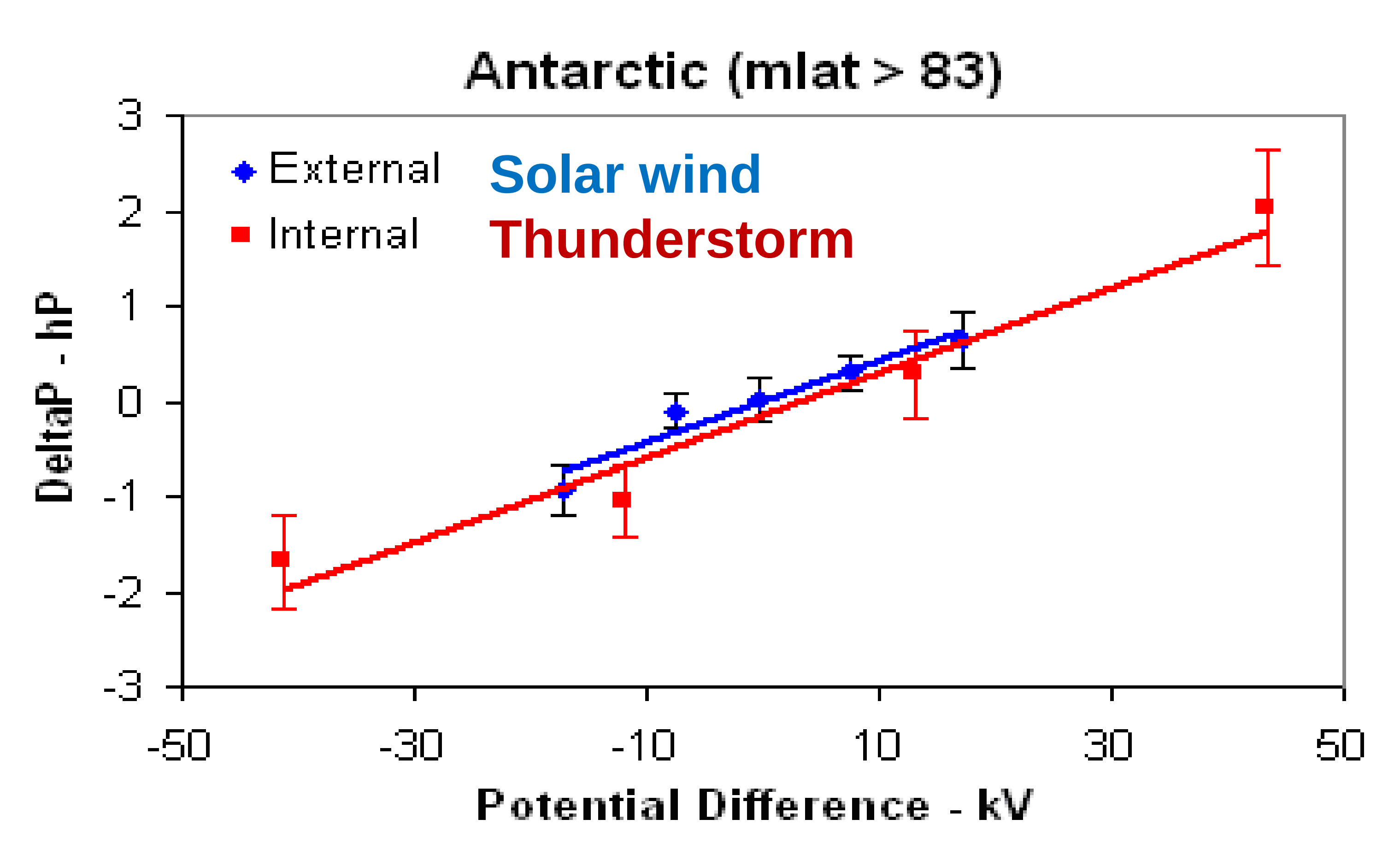


(potential gradient)

A. Global ionospheric electric potential effects

Burns et al. 2008

Surface pressure variations. Same sign N/S, similar slope to solar-wind-driven polar cap variations (later):

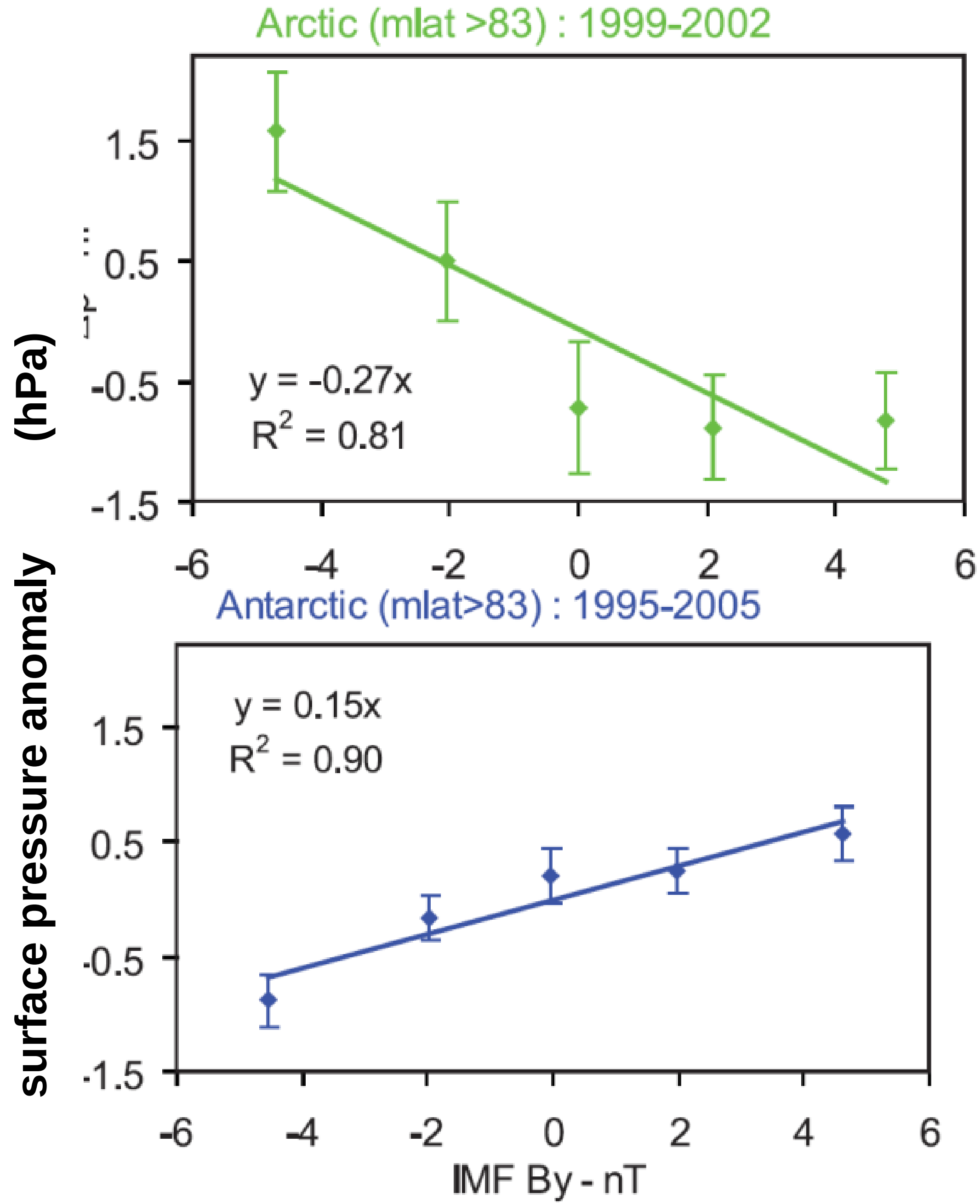


B. Polar cap ionospheric electric potential effect

Burns et al. 2008

Surface atmospheric pressure anomalies from seasonal value

Well-established effect



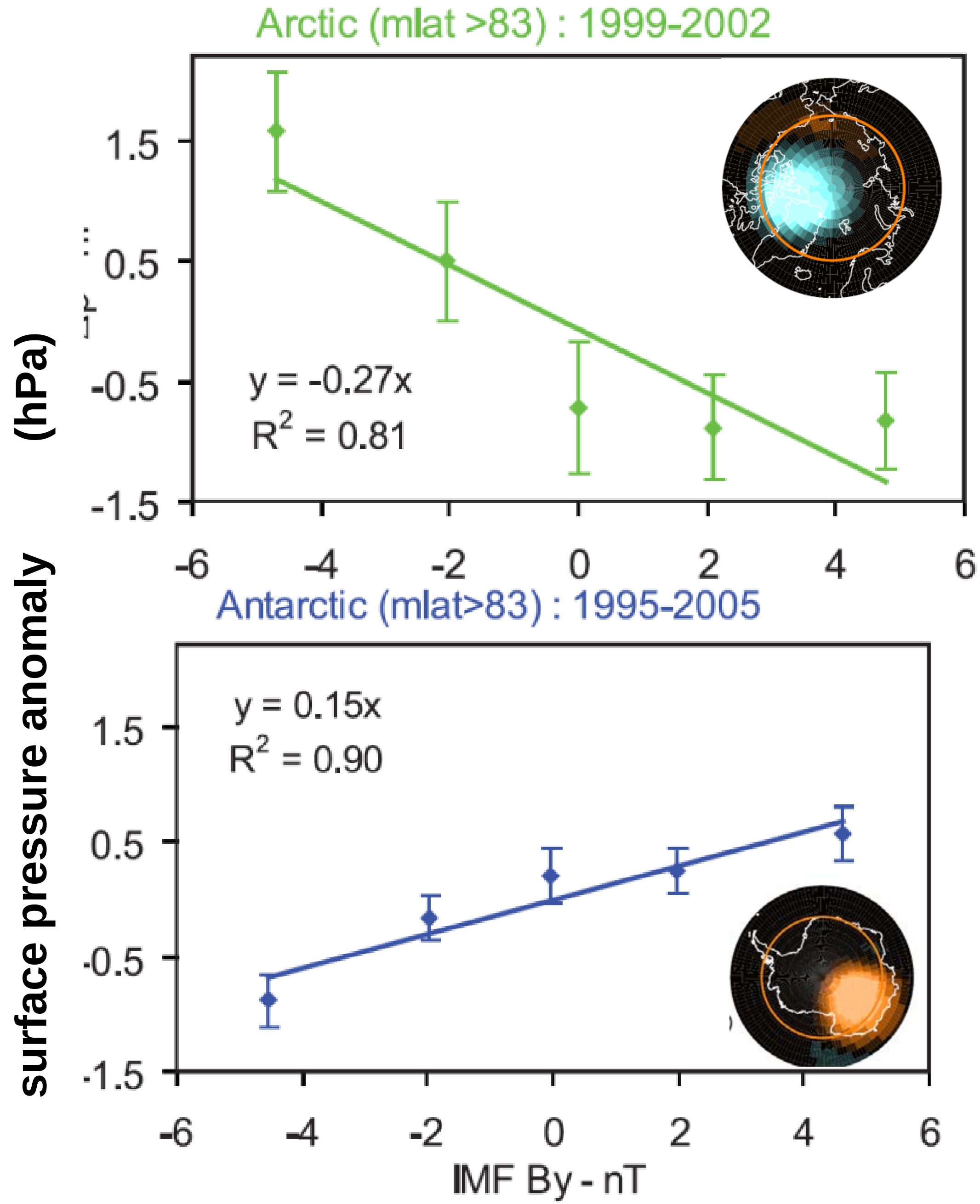
B. Polar cap ionospheric electric potential effect

Burns et al. 2008

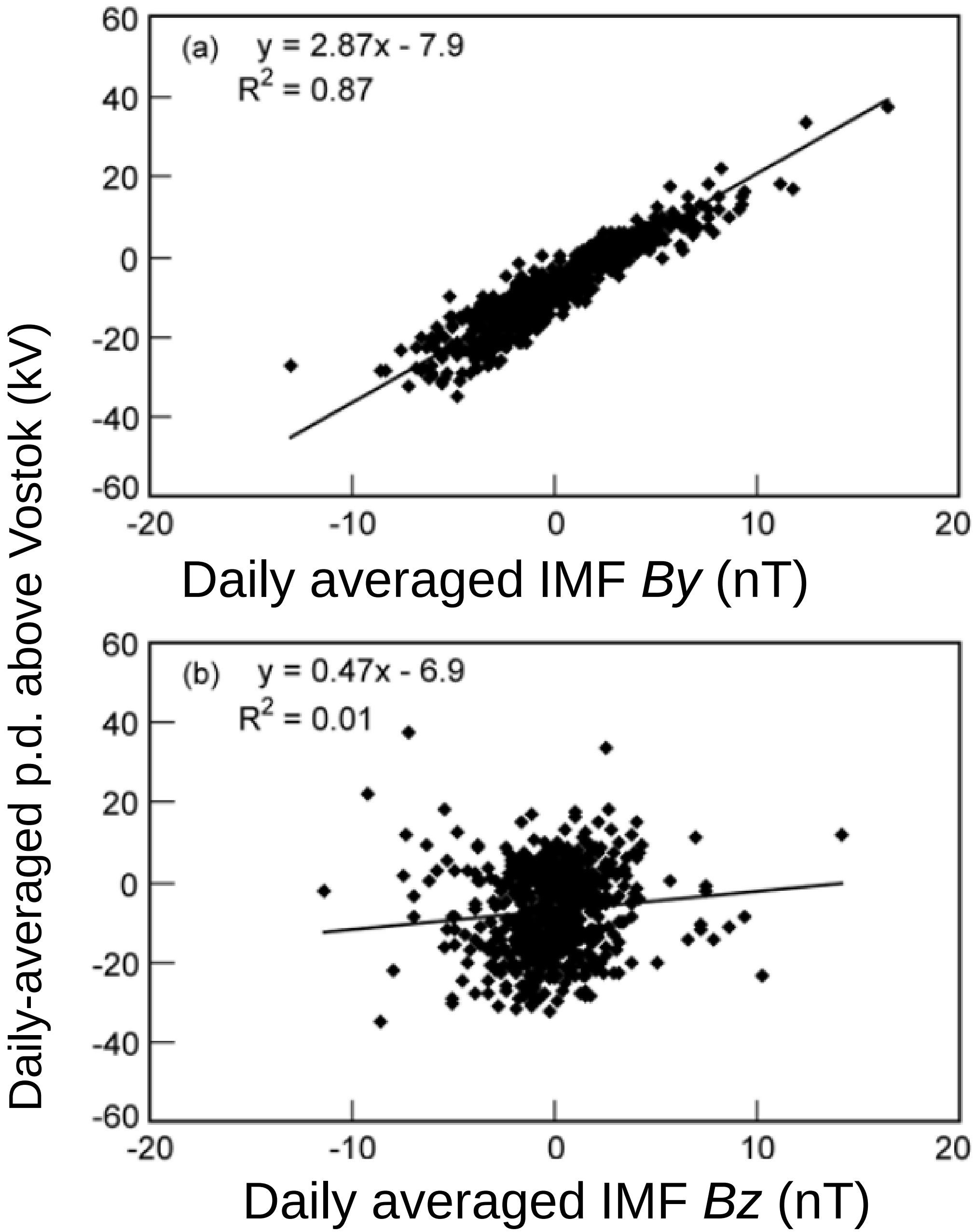
Surface atmospheric pressure anomalies from seasonal value

Change of Δp and Φ_{SW} with increasing IMF B_y **has same sign** within a given hemisphere

-ve in N
+ve in S



B. Dependence on B_y and B_z: indication of *daily* timescale



- 87% of modelled *daily* p.d. controlled by daily-averaged B_y
- < 1% controlled by daily-averaged B_z

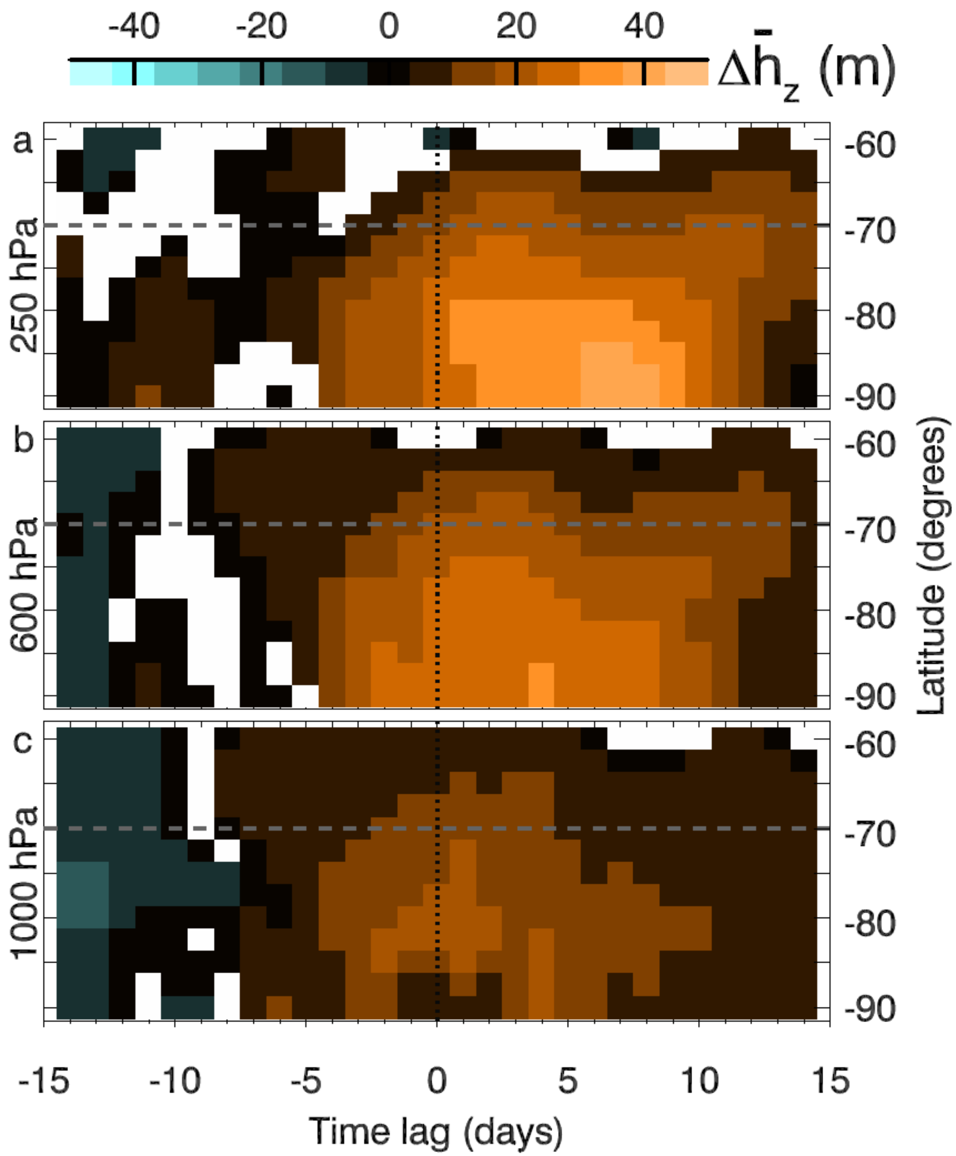
$\Rightarrow$ daily timescale

Empirical Weimer model (satellite, B_y, B_z, v) on Antarctic plateau

Burns et al. 2007

B. Zonal mean of difference between IMF B_y states

$$\Delta\bar{h}_z(\lambda,p,\tau) = \bar{h}_{z+}(\lambda,p,\tau) - \bar{h}_{z-}(\lambda,p,\tau)$$

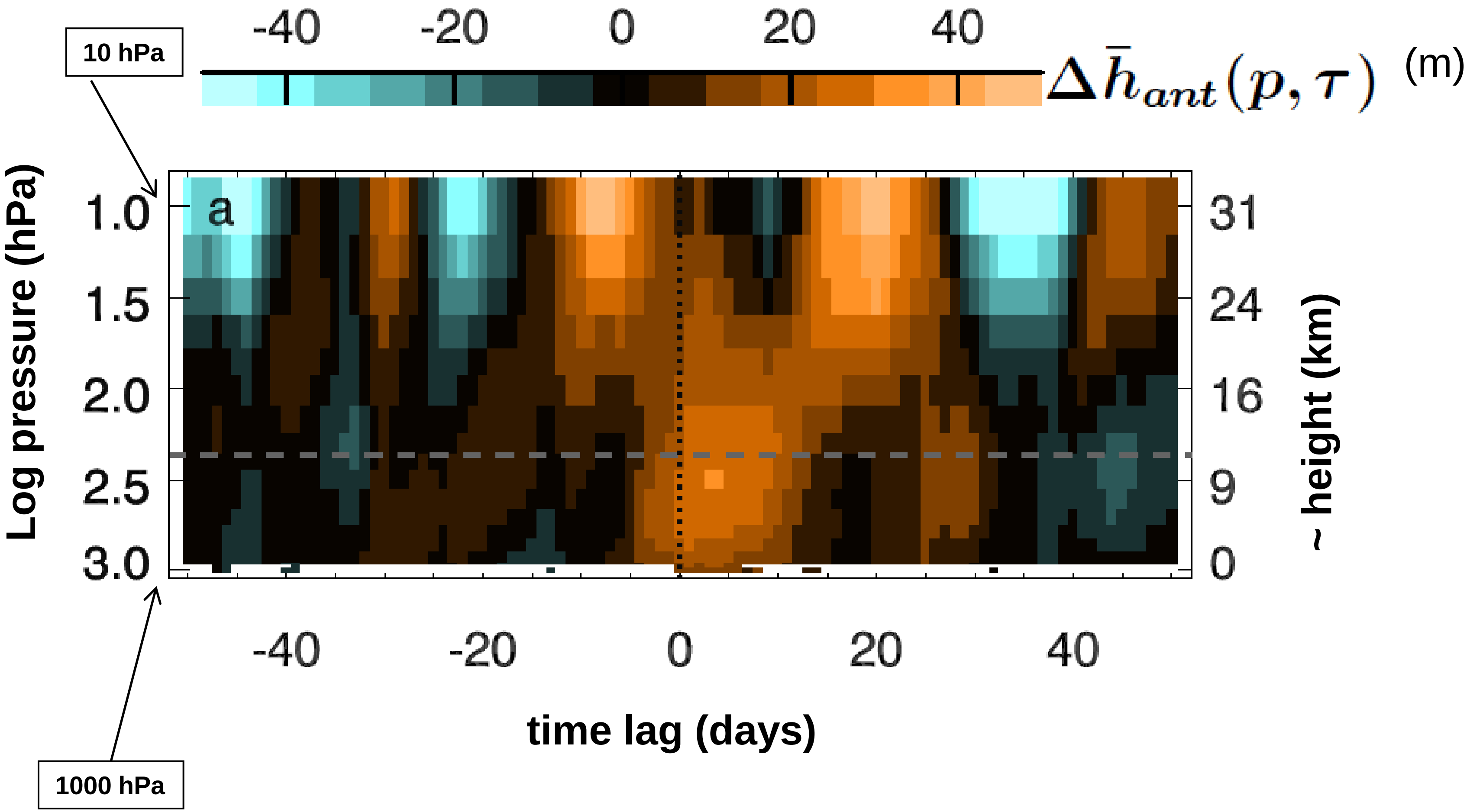


- Ordered by B_y in polar troposphere (~ 0 - 10 km)
- Time lag of peak correlation, between solar wind and atmosphere, *increases with increasing altitude*

1% probability-level mask
No data used below topography

Lam et al. 2014

B. Variation with height: field mean ≥ 70° S



Difference of mean geopotential height anomaly for 2 B_y bins

Lam et al. 2014

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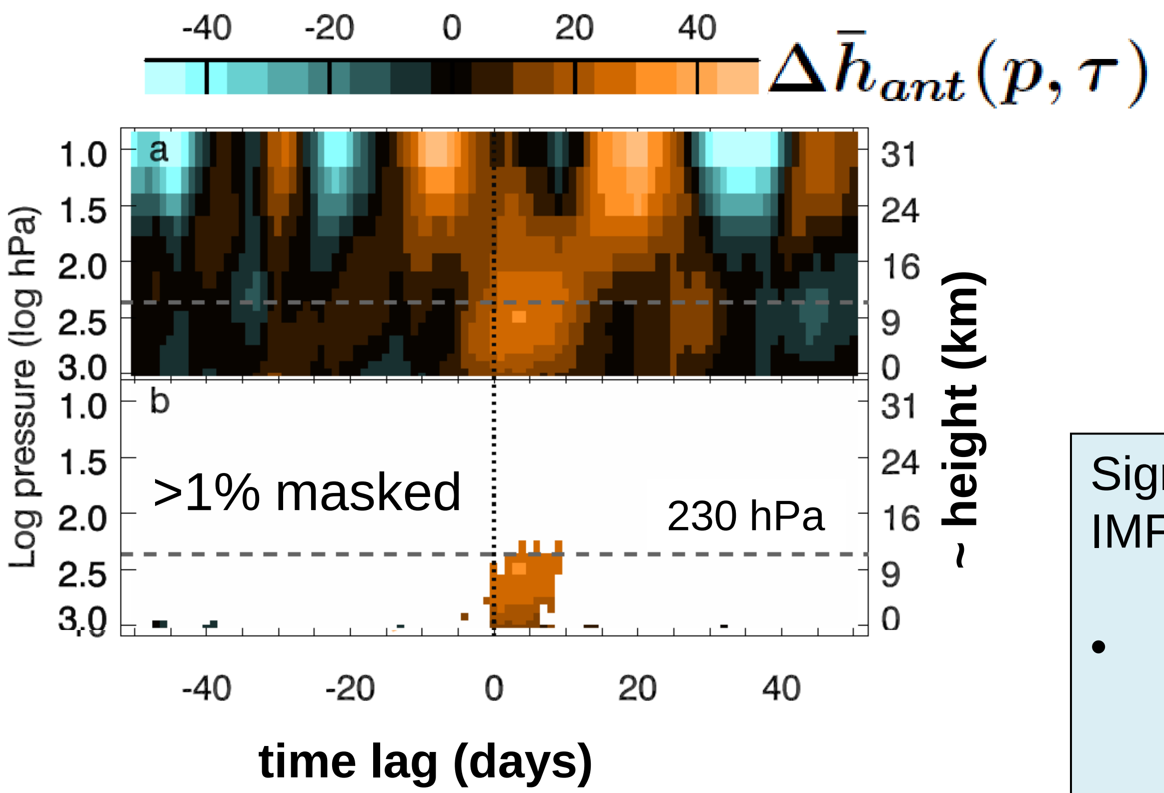

Difference of mean geopotential height anomaly for 2 B_y bins

Significant correlation (1%) of IMF B_y and geopotential height:

- in troposphere and base of stratosphere
- for ~10 day interval, peaking for time lag > 0 (solar wind leads atmosphere)

Lam et al. 2014

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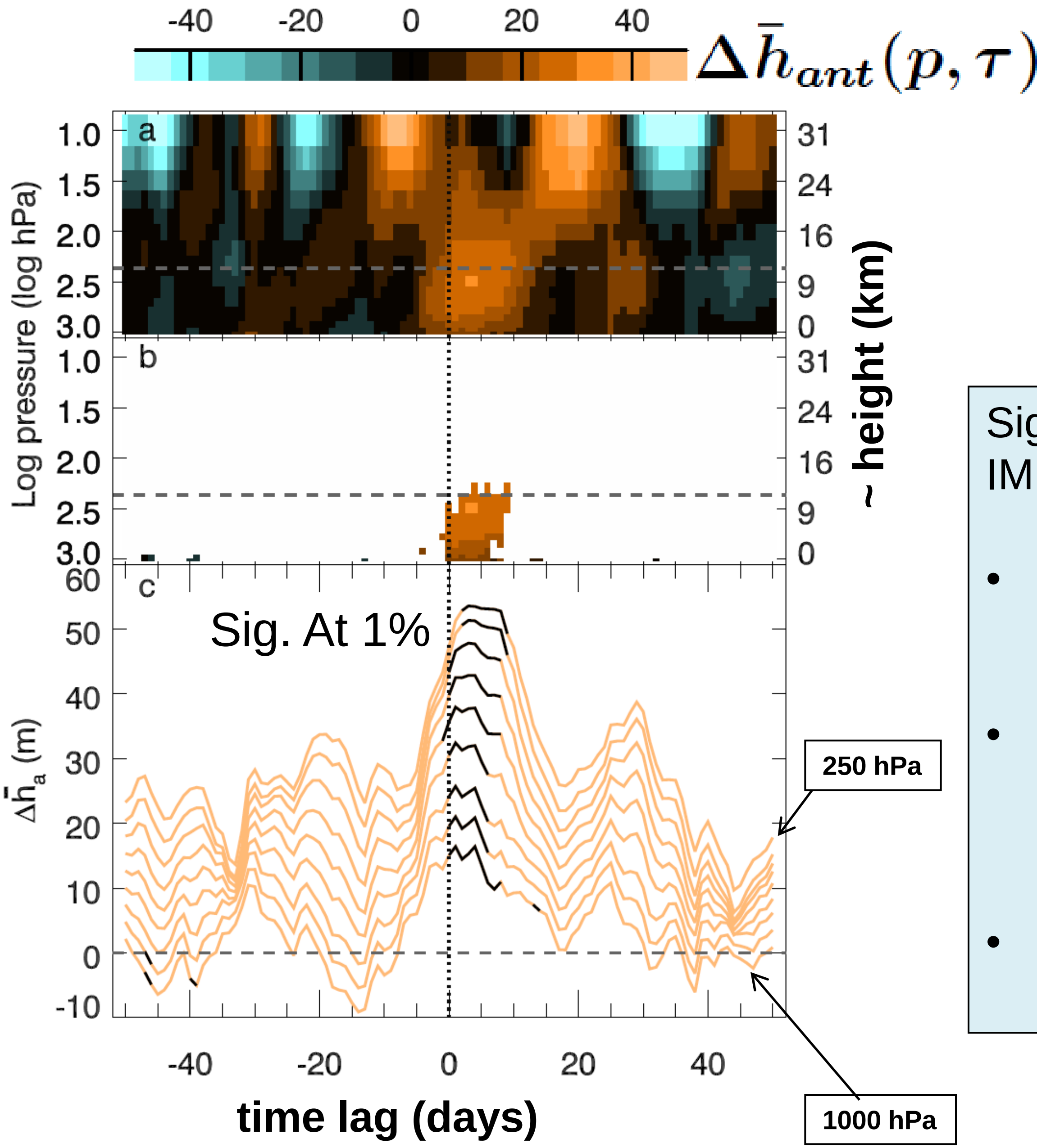

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- for ~10 day interval, peaking for time lag > 0 (solar wind leads atmosphere)
- time lag of peak increases with altitude

Lam et al. 2014

C. Relativistic electron flux effect (Wilcox effect)

Wilcox et al. 1973, Hinds and Halevy 1977; Larsen and Kelly

- Reduction of high vorticity in winter storms at times of solar wind heliospheric current sheet crossing

- Reduction in quasi-trapped relativistic electron flux (REF) precipitating from sub-auroral latitudes

- If R_M not negligible wrt R_T , Δ REF $\Rightarrow \Delta J_z$
  Strength of the effect depends on sulfuric acid aerosol in middle atmosphere.

- Recently confirmed:
  Tinsley et al 2012; Mironova et al. 2012, Zhou et al 2013

Well-established effect

D. Solar energetic particle (Veretenenko) effect

Veretenenko and Thejll 2004, 2005

Observed increase in tropospheric vorticity that accompanies solar energetic particle events – associated with increase in J_z *(Roble and Tzur 1986)*

Mironova et al. 2012

Possible effect of ionization associated with extreme SEP event on stratospheric aerosols. Marginally detectable but statistically ‘robust’.

Veretenenko and Thejll 2013

Intensification of cyclonic activity mainly over oceans associated with 90 MeV SEP events during colder half of the year in regions characterized by high temperature contrasts

Artamonova and Veretenenko 2013b

Changes in zonal and meridional circulation patterns associated with decreases in GCR flux

E. Forbush decrease (Roberts) effect

Duell and Duell 1948, Roberts and Olsen 1973; Padgoanker and Arora 1981

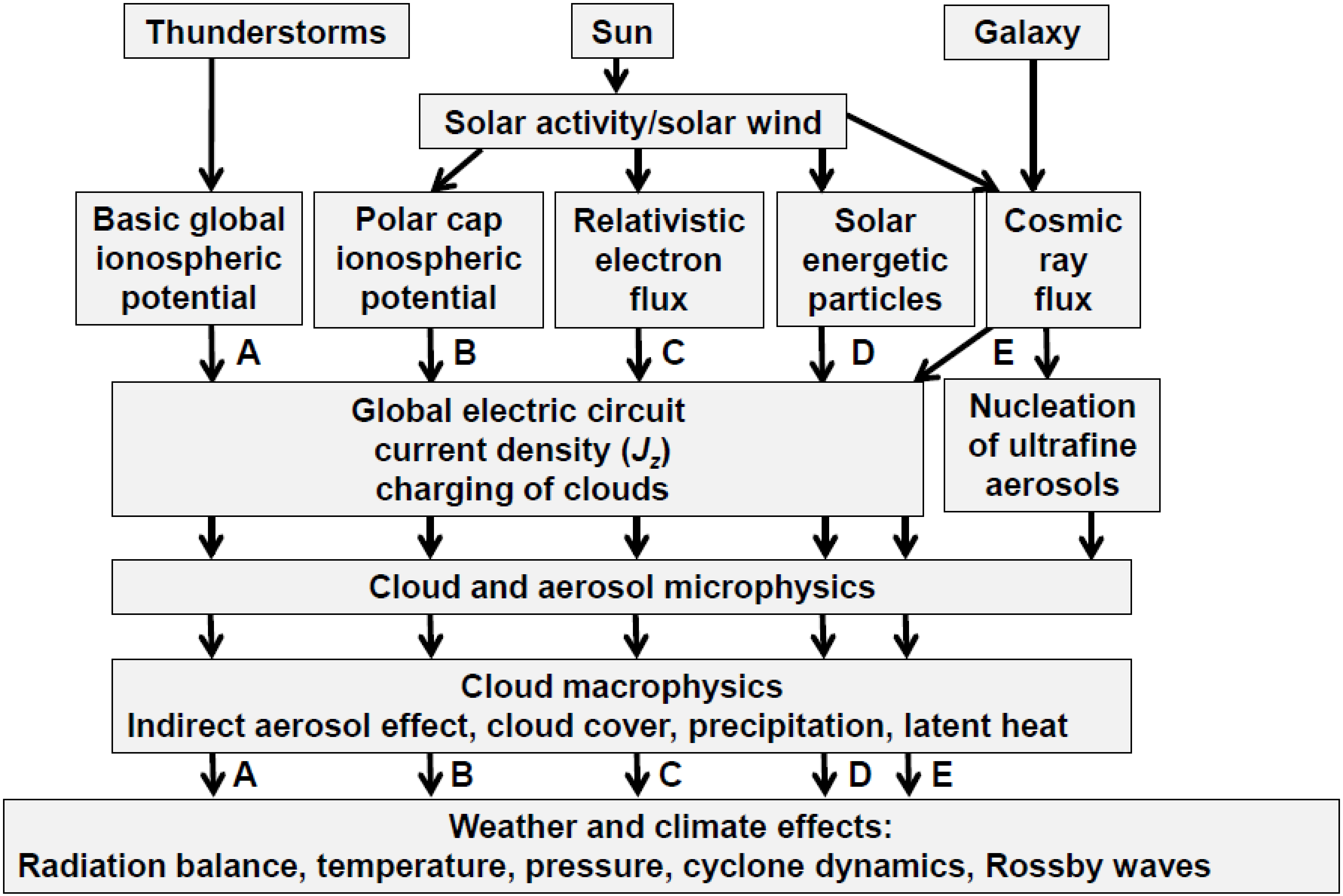
Correlation of surface pressure changes in winter storms with geomagnetic storms

More direct relationship is changes in area of high tropospheric vorticity in winter storms with GCR flux (J_z)

Artamonova and Veretenenko 2013a

Increase in pressure at mid latitudes and decrease in pressure at high latitudes associated with decreases in GCR flux

J_z as common element in day-to-day correlations



Overview

- Evidence for the electrical connection:

  Day-to-day timescale unique to electrical connection

  Dynamic responses to 4 independent space weather inputs + 1 tropospheric input, with only current density (J_z) in common

- Qualitative account of the connection:

  Global circuit models account for location and timing of responses

- Models needed: Charging of clouds

  Charging of layer clouds

  Charging of convective and cyclonic clouds

- Models needed: Electrical effects on cloud microphysics

  Five pathways to microphysical changes

- Models needed: Connection to global circulation

  To account for observed NAO and AO responses on day-to-day and inter-annual timescale, blocking, and storm track changes