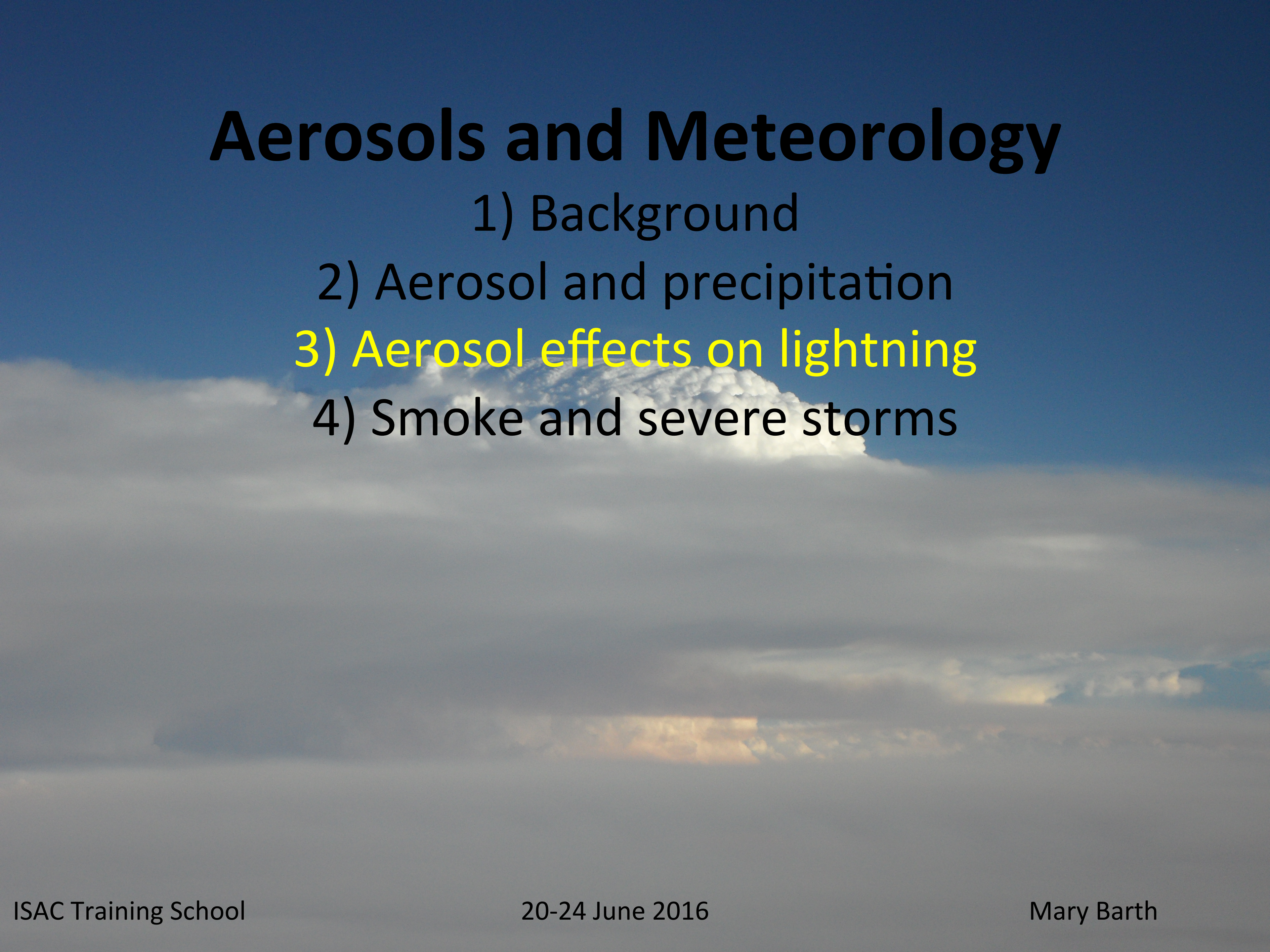
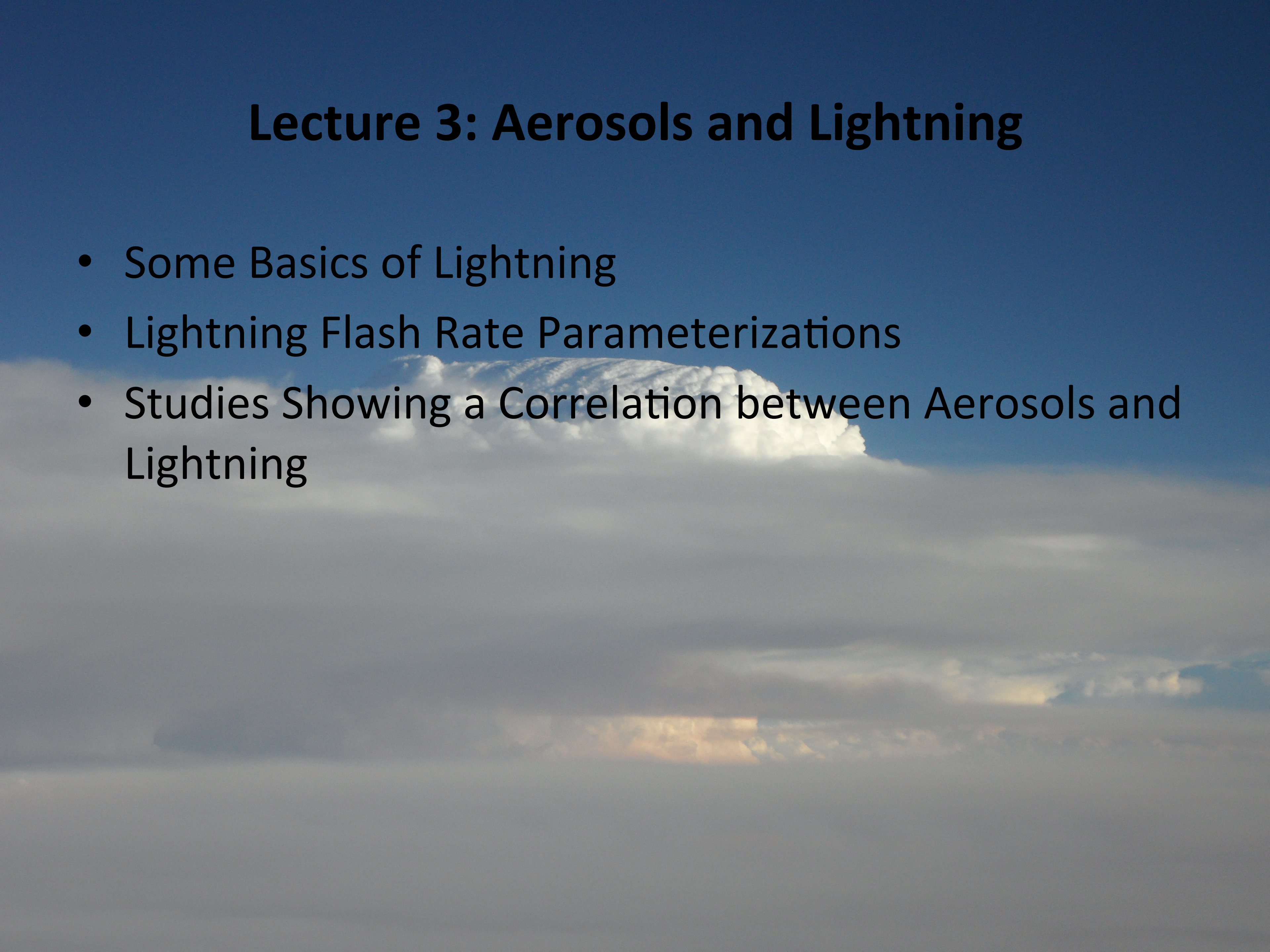


Aerosols and Meteorology

1) Background
2) Aerosol and precipitation
3) Aerosol effects on lightning
4) Smoke and severe storms



Lecture 3: Aerosols and Lightning

- Some Basics of Lightning
- Lightning Flash Rate Parameterizations
- Studies Showing a Correlation between Aerosols and Lightning

Why Predict Lightning Flashes?

Forecasting for Safety

- Humans, infrastructure, …

Forecasting for Chemistry

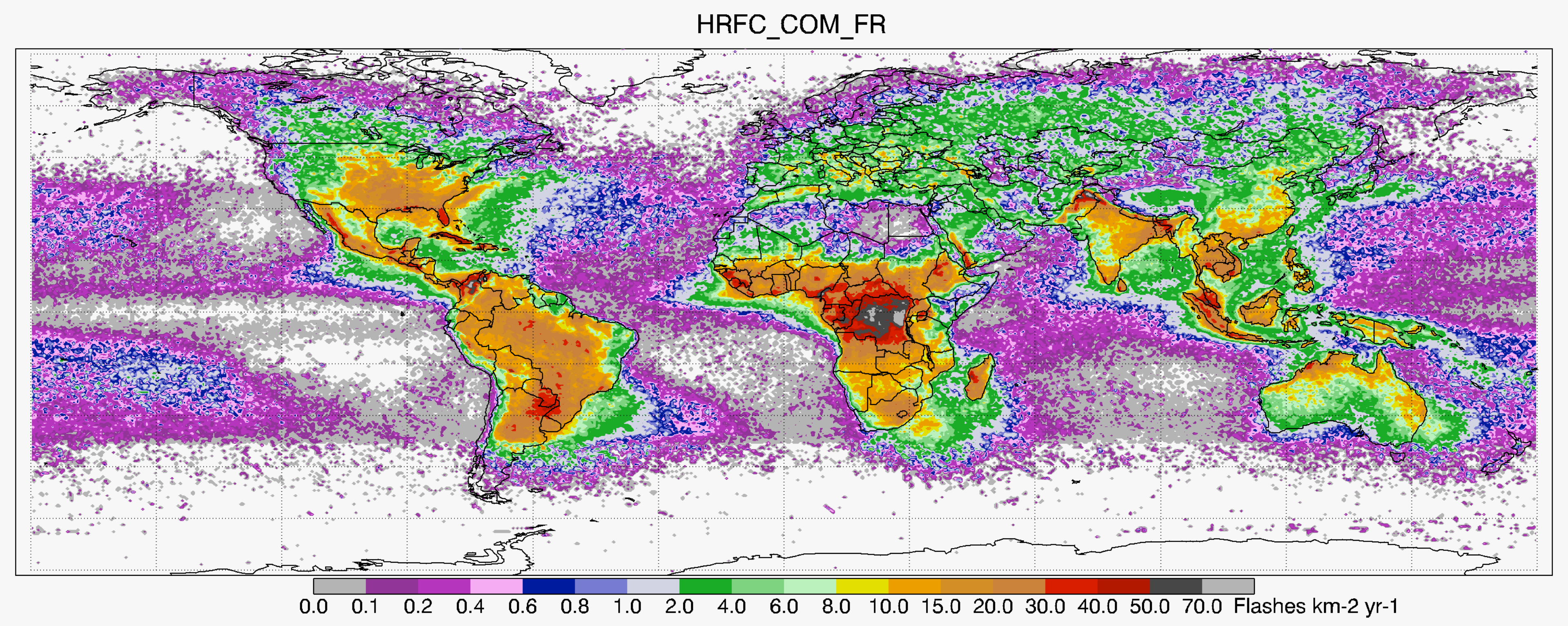
- Lightning causes temperature to increase to 1000s of degrees
- Splits molecules, including N_2 and O_2

$N + O_2 \rightarrow NO + O$
$O + N_2 \rightarrow NO + N$

→ NO production then goes on to create O_3

→ O_3 in the upper troposphere acts as a GHG

Annual number of lightning flashes based on observations from NASA satellites.



Estimate of 40 flashes per second worldwide – based on NASA satellite research of ~2000 thunderstorms at any given time (14.5 million storms each year)

Lightning Formation

Charge Separation

- Side-by-side updrafts and downdrafts
- Updrafts transport cloud droplets towards top of storm
- Downdrafts with falling hail and graupel
- Graupel – water collisions creating a “soft shell” graupel or hail particle
- Further graupel – drop collisions cause electrons to shear off of the ascending water droplets and collect on the falling ice particles

➢ Charge separation with negative charge in lower cloud and positive charge in upper part of storm

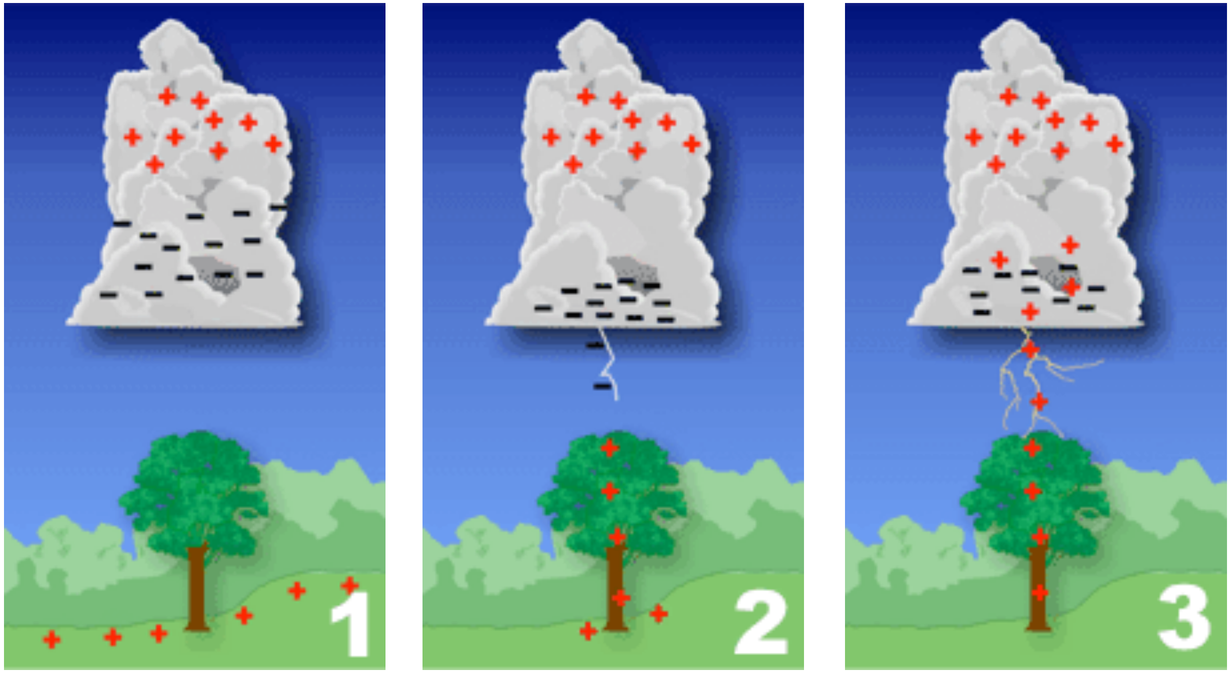
http://www.srh.weather.gov/srh/jetstream/lightning/lightning.html

Lightning Formation

Triggering Lightning

- Atmosphere is a good insulator – inhibits electric flow

1. Tremendous amount of charge must build up to overcome the atmosphere’s insulating properties and trigger lightning
2. Charge attraction to positive charge in ground
3. Cloud-to-ground negative lightning



http://www.srh.weather.gov/srh/jetstream/lightning/lightning.html

Lightning Types

Cloud-to-ground negative lightning

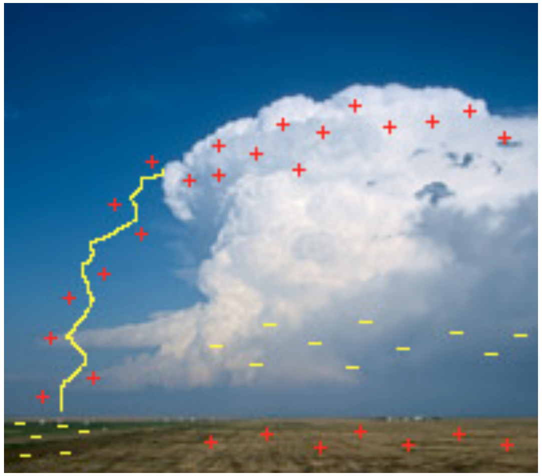
Cloud-to-ground positive lightning

Intracloud lightning

Cloud-to-ground positive lightning

- Positive lightning < 5% of all strikes
- Have 10x greater electric field
- Amount of air it must burn through is greater than that for neg. CG ltng
- May be responsible for most forest fires and power line damage

© Radek Dolecki



http://www.weatherimagery.com/blog/positive-negative-lightning/

Detecting Lightning Flashes

Commercial Lightning Detection Networks

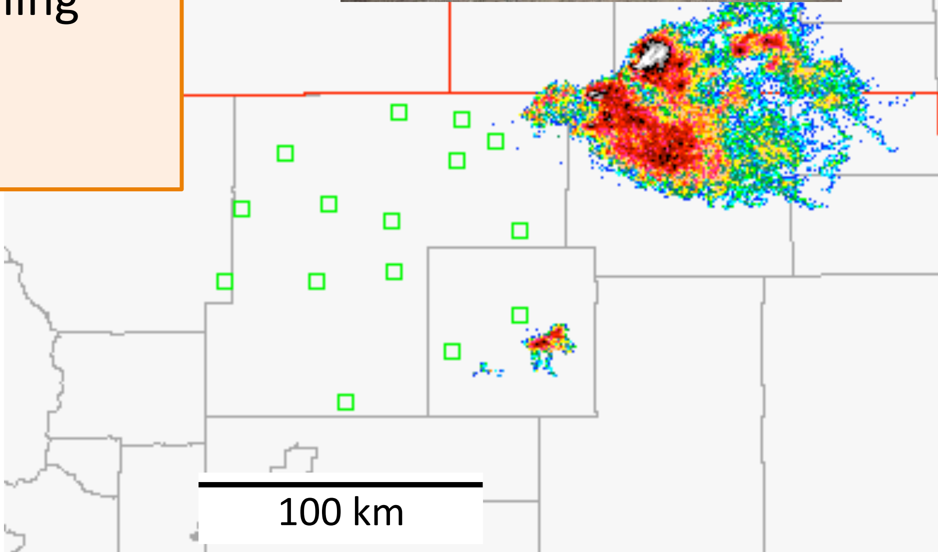
- Very high frequency (VHF) electromagnetic wave (30 – 300 MHz)

Lightning Mapping Array

- Three-dimensional mapping of lightning channel segments (VHF detection)

Geostationary Lightning Mapper (GLM)

- Satellite instrument mapping total lightning (near-IR optical detection)



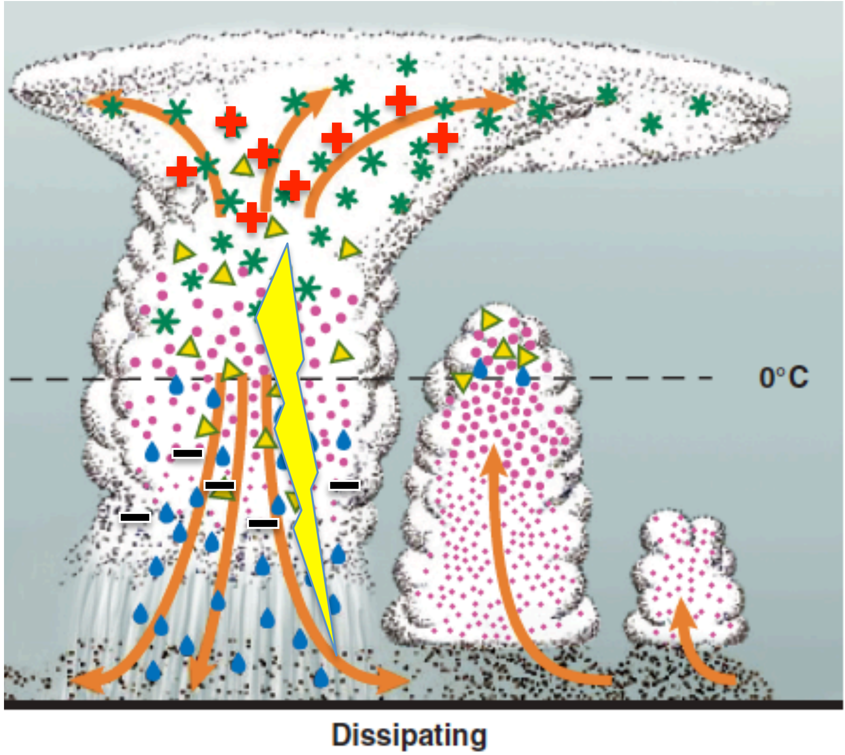
Predicting Lightning Flashes

Forecasting for Safety

- Cloud-to-ground lightning
- Lightning potential

Forecasting for Chemistry

- Total lightning
- Lightning flash rate
- Lightning flash length (or extent)
- Lightning current



graupel – drop collisions separate charge

→ Parameterizations are a function of storm characteristics

Schematic from Rosenfeld et al. (2008)

Predicting Lightning Flash Rate

Parameterized prediction:

– Williams (1985)	cloud top height (of 20 dBZ echo)
– Price and Rind (1993)	maximum vertical velocity
– Deierling (2006);	precipitation ice mass
– Wiens et al. (2005)	updraft volume
– Deierling et al. (2008)	ice mass flux product
– Petersen et al. (2005)	ice water path
– Basarab et al. (2015)	volume of 35 dBZ region

Precipitating ice = mostly graupel and hail but includes snow

Ice mass flux product

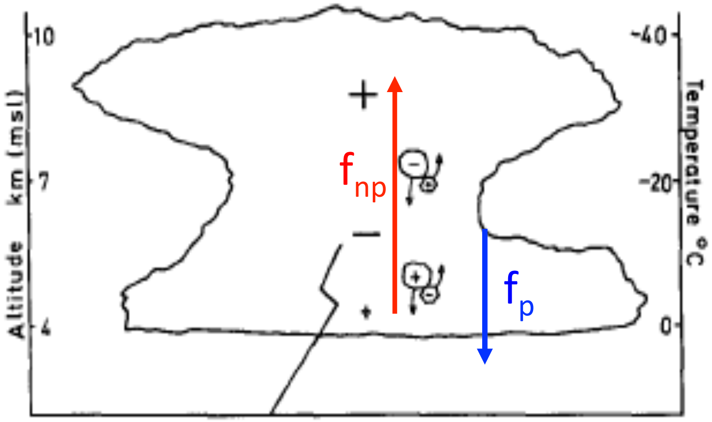


FIG. 2. A schematic of graupel–ice-crystal charge transfer above and below the reversal temperature level in a thunderstorm.

Do Aerosols Change Lightning Flash Rate?

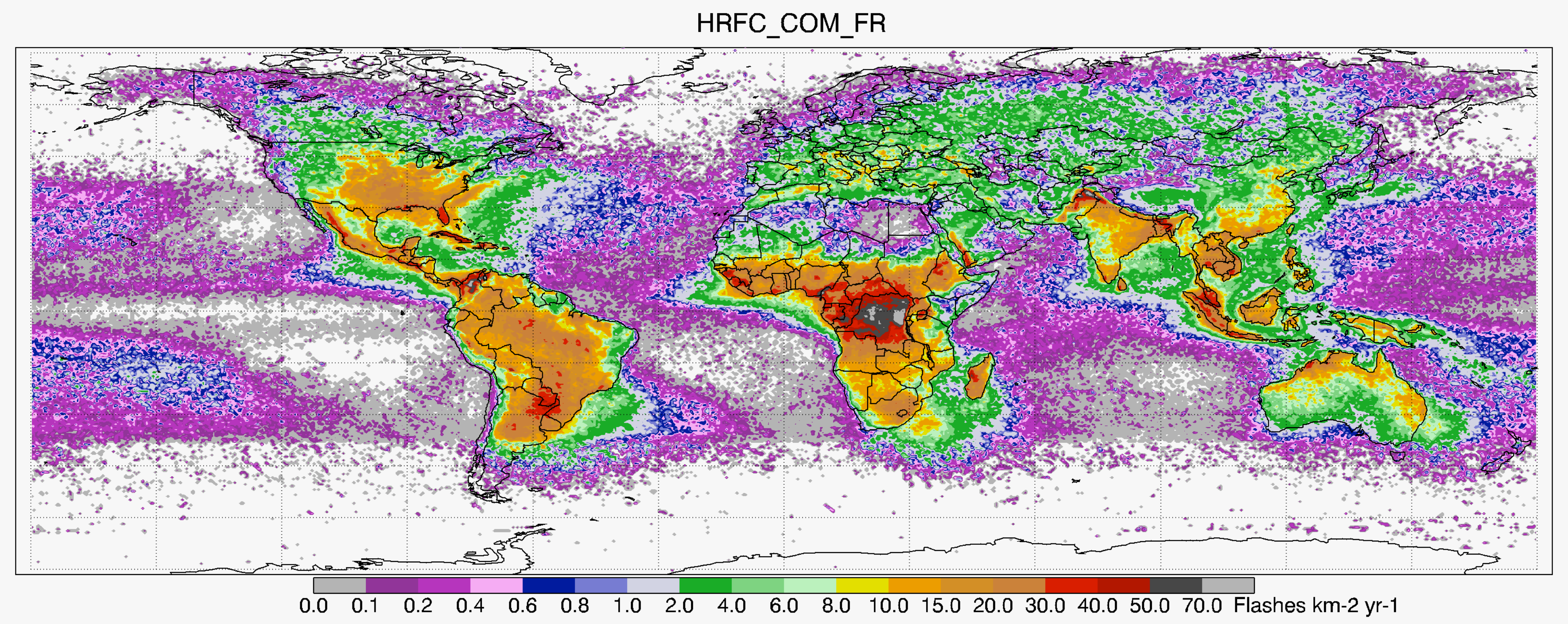
Parameterized prediction:

Williams (1985)	cloud top height
Price and Rind (1993)	maximum vertical velocity
Deierling (2006);	precipitation ice mass
Wiens et al. (2005)	updraft volume
Deierling et al. (2008)	ice mass flux product
Petersen et al. (2005)	ice water path
Basarab et al. (2015)	volume of 35 dBZ region

Challenge: Predicting the storm physics and dynamics well in order to use these empirical relationships

If aerosols affect the cloud physics and dynamics, then they likely affect the lightning flash rate

Annual number of lightning flashes based on observations from NASA satellites.



Estimate of 40 flashes per second worldwide – based on NASA satellite research of ~2000 thunderstorms at any given time (14.5 million storms each year)

Lightning (convective intensity) Variability

(Rosenfeld et al., 2008)

Thermal Hypothesis as to why lightning varies

- Differences in thermodynamic instability
- CAPE, low-level shear but, CAPE is similar over land and ocean

Aerosol Hypothesis as to why lightning varies

- Number of CCN influences microphysical and vertical development of convective clouds → convective invigoration
- At CCN > 500 cm^{-3}, collision-coalescence mechanism hinders precipitation formation (relative to low CCN case)
- More cloud water transported to mixed phase region, causing more latent heat (when drops freeze), stronger updrafts, & greater charge separation

Rosenfeld et al. (2008) *Science*

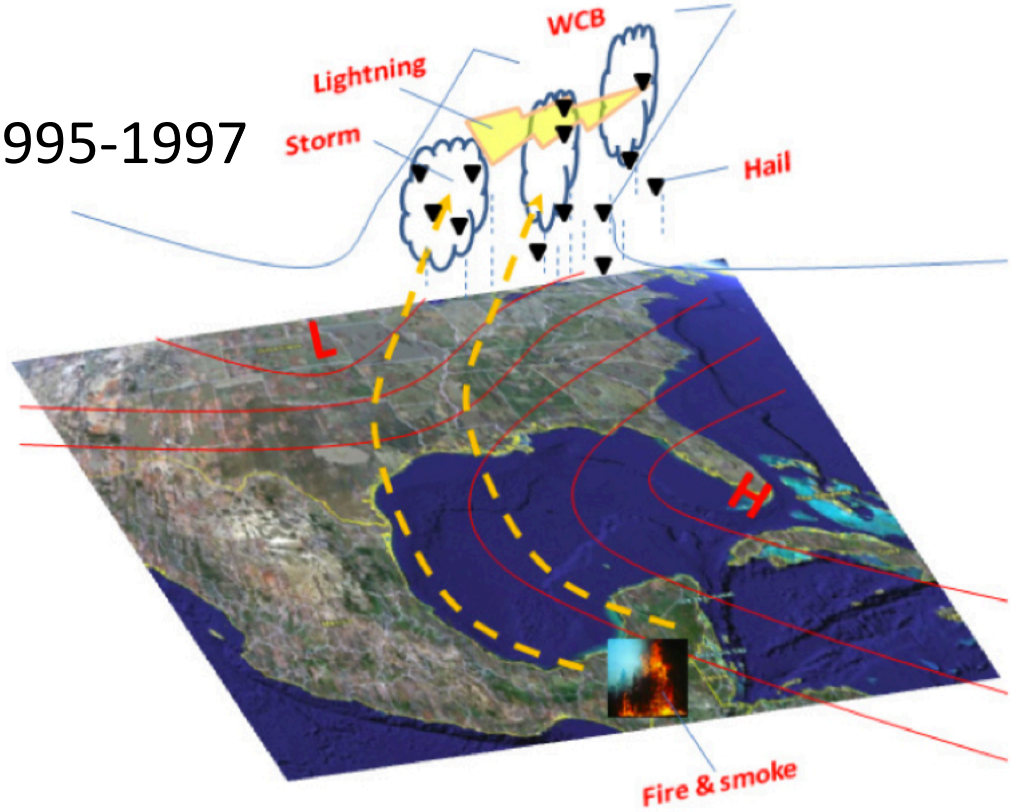
Effect of Pollution from Central American Fires on CG Lightning in May 1998 (Murray et al., 2000)

Spring 1998

- El Nino: 1997-1998
- Central American Fires

Compared May 1998 to May 1995-1997 and 1999

- Percentage positive flashes
- Peak currents
- Number of strokes per flash



Murray et al. (2000) *Geophys. Res. Lett.*

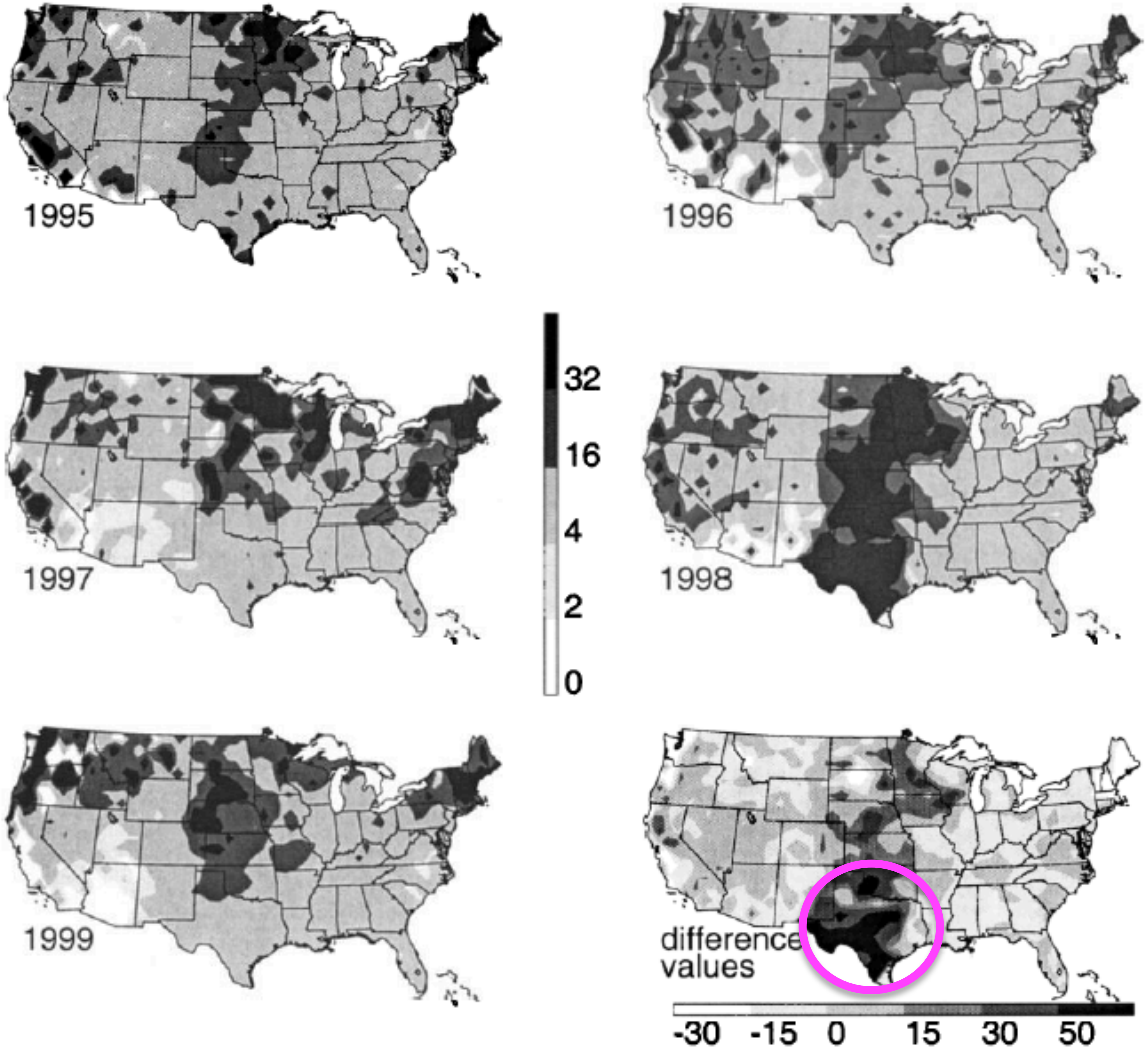
Effect of Pollution from Central American Fires on CG Lightning in May 1998

- Percentage positive flashes by year ↑
- Peak currents

  Negative flash ↓ by 12 kA

  Positive flash ↑ by 20 kA
- Number of strokes per negative flash ↓

→ Suggest aerosols from fires may be affecting lightning characteristics



Murray et al. (2000) *Geophys. Res. Lett.*

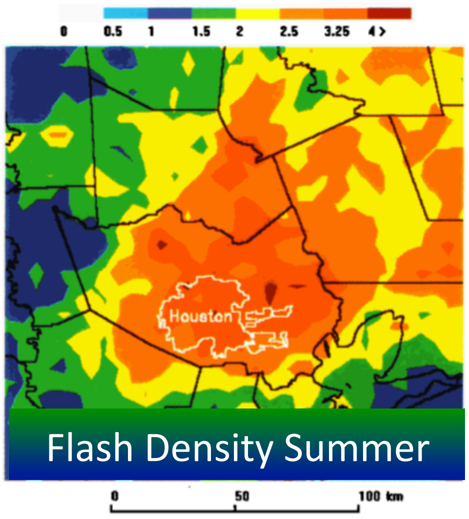
Enhancement of Cloud-To-Ground Lightning over Houston, Texas (Orville et al., 2000)

1989-2000 NLDN CG flash densities:

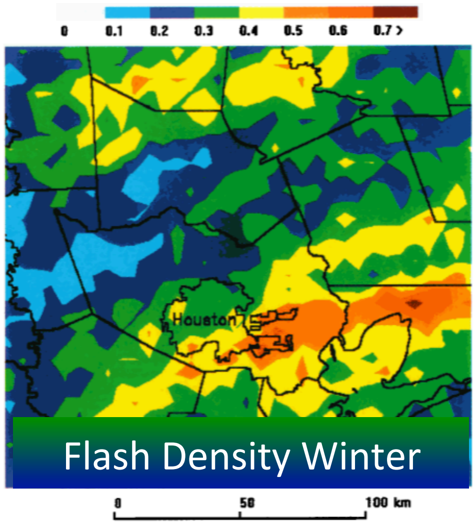
- 4 flashes km^{-2} in JJA
- 0.7 flashes km^{-2} in DJF

Higher in summer than winter

- Convergence due to urban heat island
- Increasing levels of aerosols that enable more cloud water to reach the mixed phase region enhancing separation of electric charge and lightning (discussed but did not provide analysis or modeling to show likelihood)



Flash Density Summer



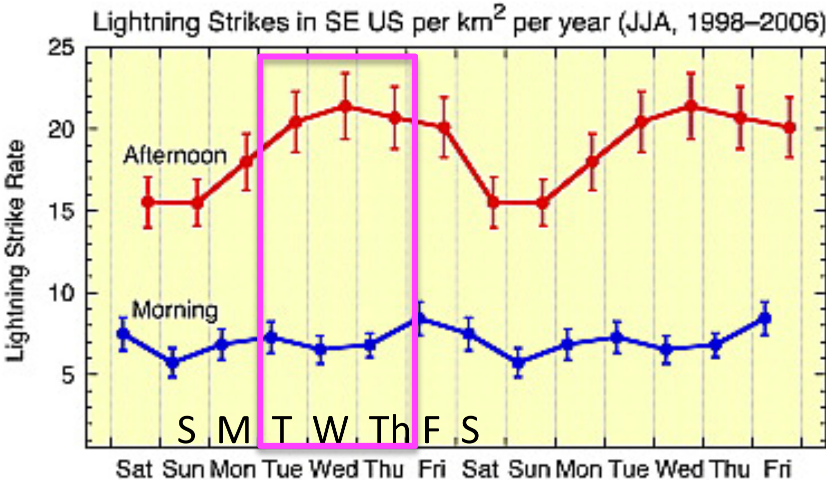
Flash Density Winter

Orville et al. (2001) *Geophys. Res. Lett.*

Weekly Cycle of Lightning: Evidence of Storm Invigoration by Pollution (Bell et al., 2009)

1998-2009 NLDN CG flash densities:

- Summer lightning activity peaks in middle of week in the southeast U.S.
- Weekly cycle reduced over population centers
- No evidence of a weekly cycle of synoptic forcing
- Conclude that aerosols cause storms to intensify in humid, convectively unstable environments



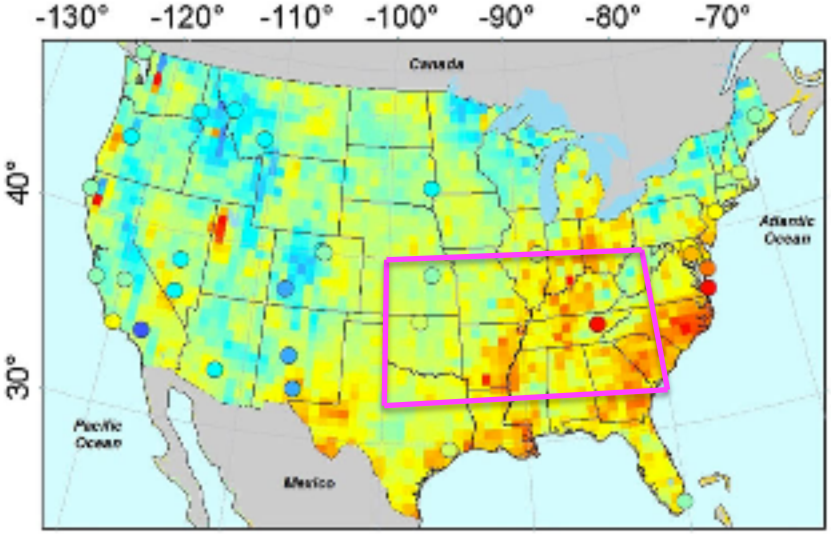
Bell et al. (2009) *Geophys. Res. Lett.*

100W-80W, 32.5N-40N

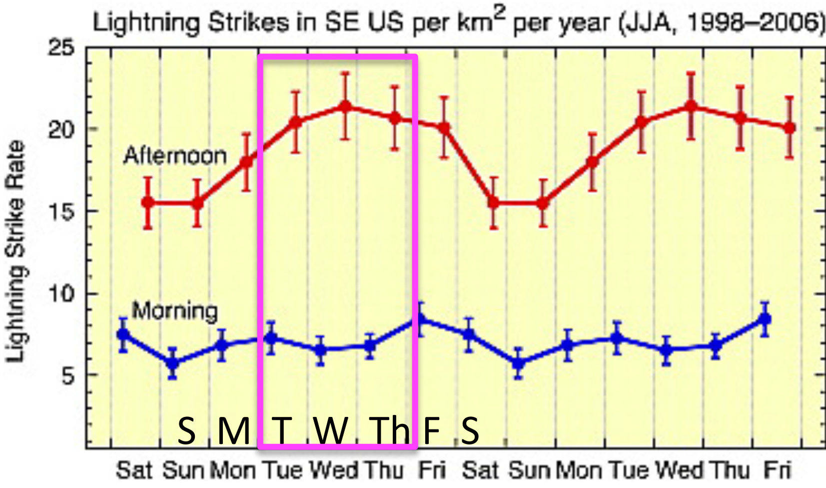
Weekly Cycle of Lightning: Evidence of Storm Invigoration by Pollution

Over this “SE U.S.” region,

- Aerosol distributions vary greatly
- May not be substantially different during week versus weekend due to emissions



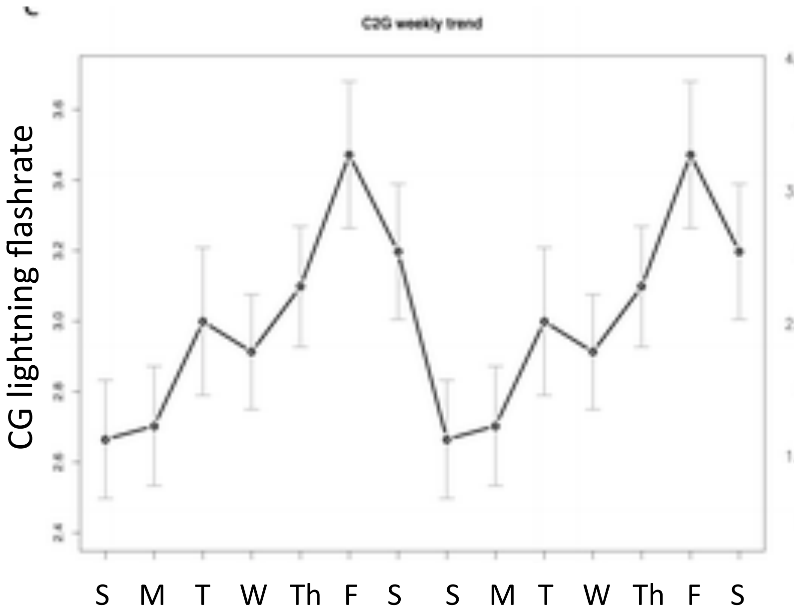
Bell et al. (2009) *Geophys. Res. Lett.*



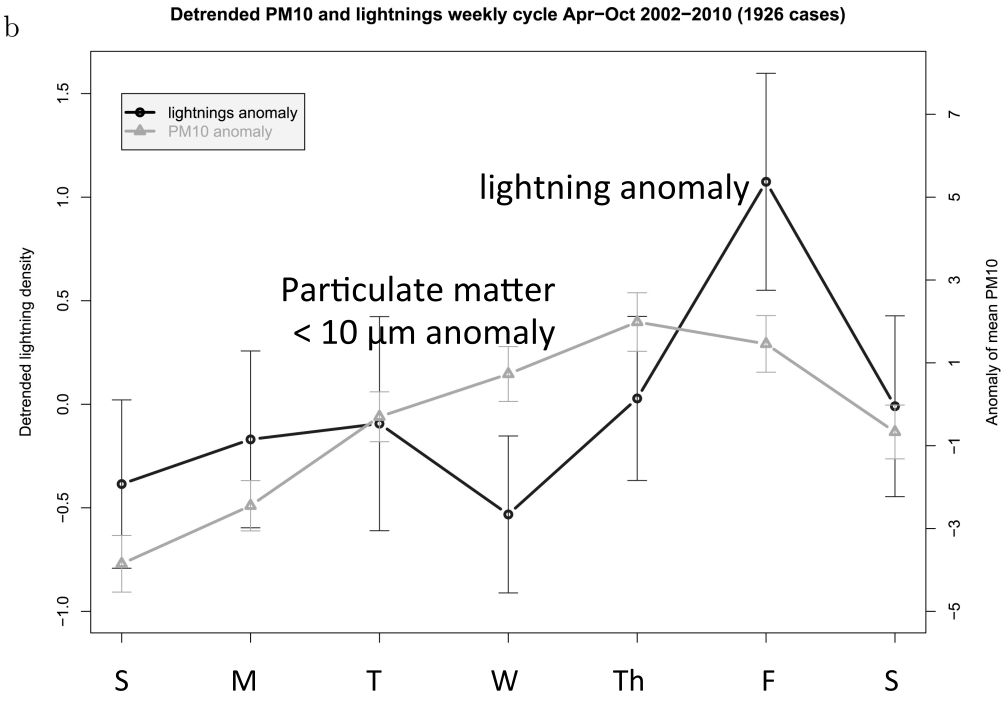
100W-80W, 32.5N-40N

Weekly Cycle of Lightning

Also seen in Northeastern Italy



Feudale and Manzato (2014)
J. Appl. Meteo. and Climate



Cloud Modeling of Storms with Lightning Prediction

Mansell and Ziegler (2013) *J. Atmos. Sci.*

Aerosol Effects on Simulated Storm Electrification and Precipitation in a Cloud Model

Use state-of-the-art cloud model (COMMAS) with storm electrification scheme (i.e. predict charge). Conduct idealized simulations of a small thunderstorm observed during the TELEX field campaign.

$N_{drop} = CCN\ S^{0.6}$

$CCN = 100\text{-}5000\ cm^{-3}$

Aerosol Effects on Simulated Storm Electrification and Precipitation in a Cloud Model

Examined effects of different CCN concentrations on a multicell convective storm

→ Shows CCN causing updraft invigoration and delay of precipitation formation (Rosenfeld et al., 2008)

→Graupel Production increases with CCN rising

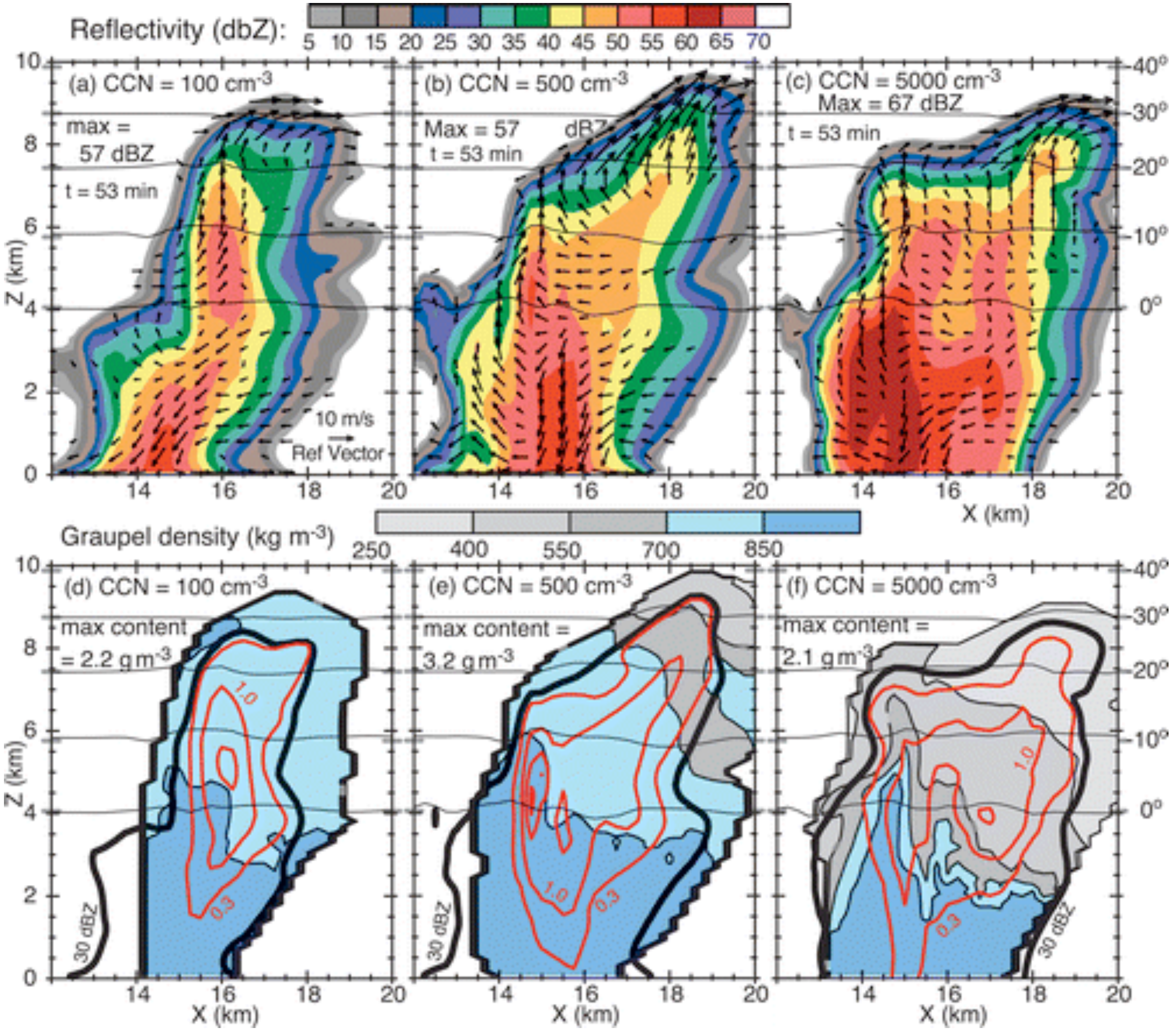
→Lightning response is weak until Hallett-Mossop rime splintering ice multiplication becomes more active (CCN > 700 cm^{-1})

→Greater CCN concentrations lead to greater lightning activity but with sensitivity to ice multiplication

Mansell and Ziegler (2013) *J. Atmos. Sci.*

Aerosol Effects on Simulated Storm Electrification and Precipitation in a Cloud Model

CCN=100 CCN=500 CCN=5000



- Storm increases in height, updraft strength at CCN = 500 cm-3
- A slightly weaker storm at CCN = 5000 cm-3

- Graupel density changes from hail-like to graupel-like for increasing CCN because smaller drops result in lower density graupel

➢ Impacts lightning

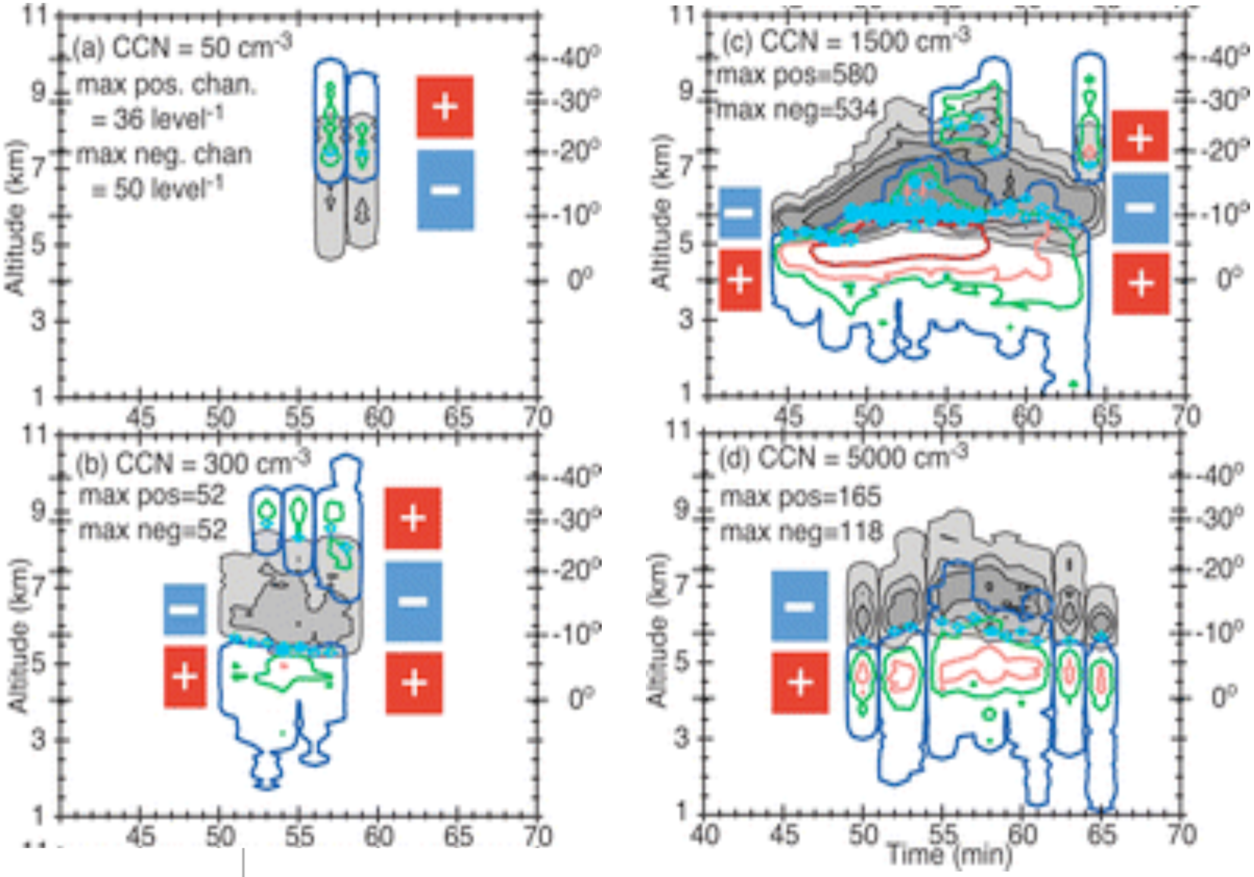
Mansell and Ziegler (2013) *J. Atmos. Sci.*

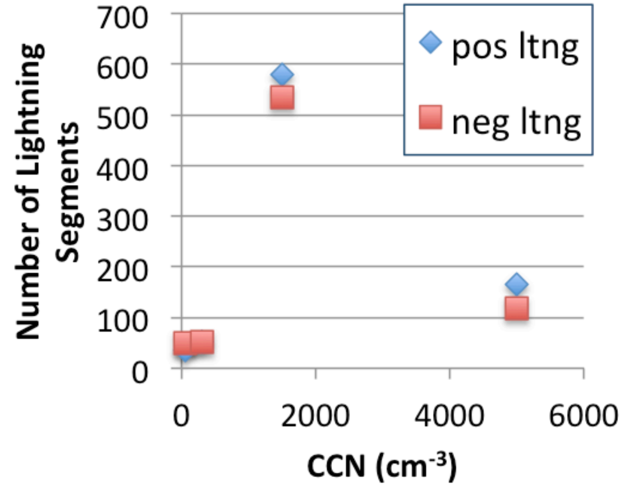
Lightning Activity Increases As More Graupel Is Generated

changes in ice crystal production play a role

Charge structure

- Low CCN, positive dipole
- Higher CCN, initially a negative dipole that become a tripole at CCN of 300-500 cm-3
- Remains a negative dipole for CCN=5000



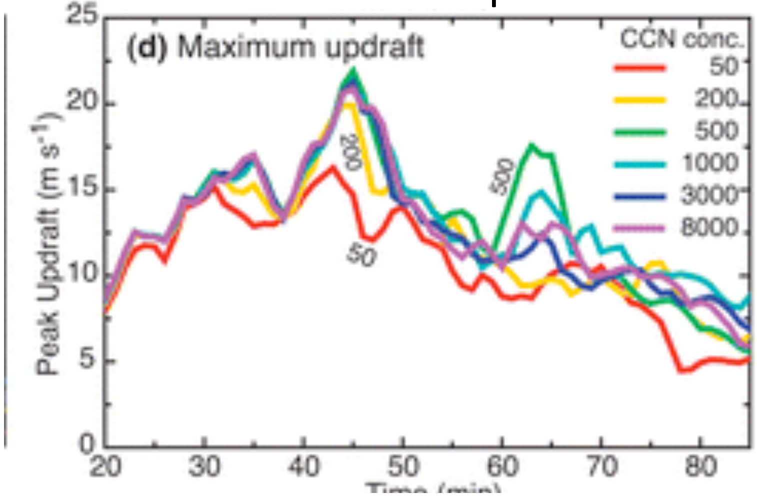


Reduction in lightning activity at high CCN is due to ice crystal generation

Mansell and Ziegler (2013) *J. Atmos. Sci.*

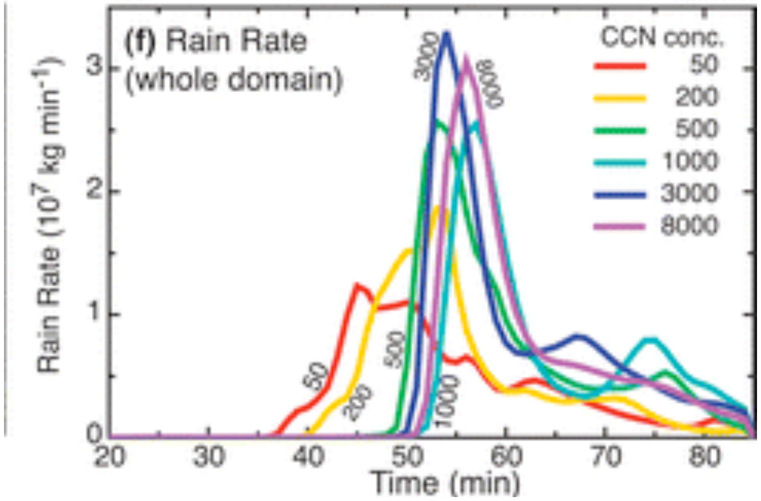
Updraft Invigoration Effect is Evident

Maximum updraft



N_{CCN}
50
200
500
1000
3000
5000

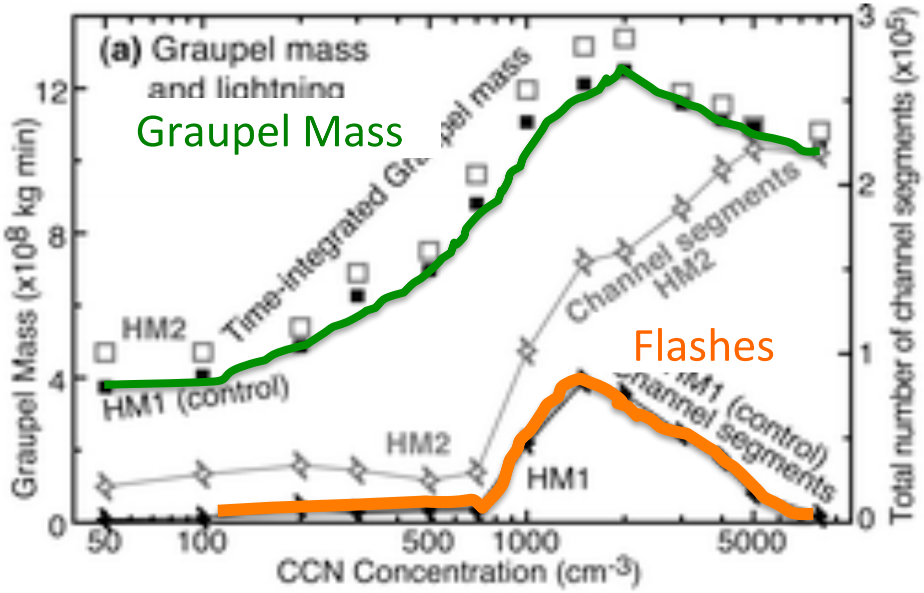
Rain Rate



Mansell and Ziegler (2013) *J. Atmos. Sci.*

- Updraft volume increases with increased N_{CCN}
- Driven by increased condensation rate
- Buoyancy affected by freezing via graupel riming and reduced water loading by sedimentation
- Rain mass highest at 500 cm^{-3}
- Rain rate is delayed for higher CCN

Lightning Flash Rates Correlated with Updraft Volume, Precipitation Ice Mass



- Graupel mass corresponds with lightning channel segments
- But decrease in lightning is greater than decrease in graupel mass – somehow graupel becomes less effective at charge separation at high CCN
- Changes in graupel mass and number cannot account for dramatic drop in lightning flashes
- Small ice crystal production from ice splintering explains drop in lightning flashes

Mansell and Ziegler (2013) *J. Atmos. Sci.*

Simulations of Convection and Lightning Found:

→ Increasing CCN causes updraft invigoration and delay of precipitation formation (Rosenfeld et al., 2008)

→Graupel Production increases with CCN rising

→Lightning response follows graupel mass which increases as CCN increases until high CCN (1500 cm-3)

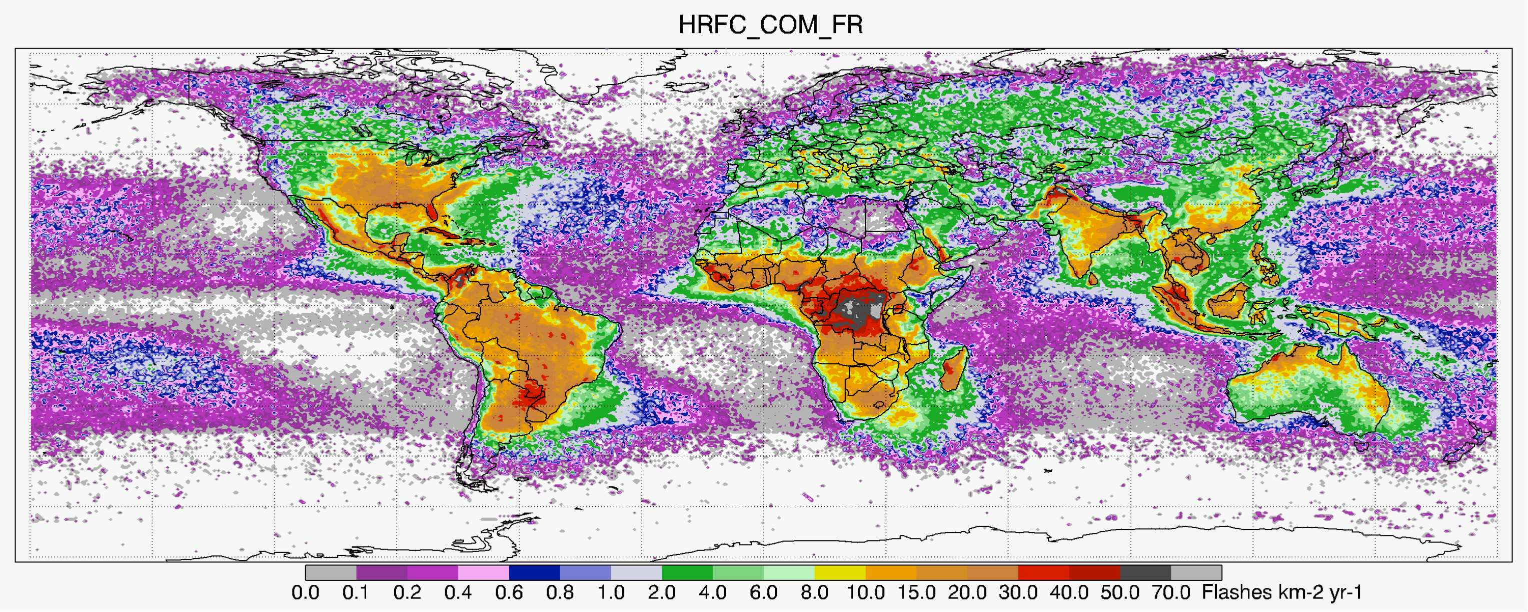
→Ice multiplication from Hallett-Mossop rime splintering process is key to understanding why lightning decreases dramatically at high CCN while graupel mass decreases more gently

→Greater CCN concentrations leads to greater lightning activity but with sensitivity to ice multiplication

Mansell and Ziegler (2013) *J. Atmos. Sci*

Simultaneous Influences of Thermodynamics and Aerosols on Deep Convection and Lightning in the Tropics

Stolz et al. (2015) *J. Geophys. Res*



Simultaneous Influences of Thermodynamics and Aerosols on Deep Convection and Lightning in the Tropics

Thermal Hypothesis as to why lightning varies

- Differences in thermodynamic instability
- CAPE, low-level shear

Aerosol Hypothesis as to why lightning varies

- Number of CCN influences microphysical and vertical development of convective clouds → convective invigoration
- At CCN > 500 cm^{-3}, collision-coalescence mechanism hinders precipitation formation (relative to low CCN case)
- More cloud water transported to mixed phase region, causing more latent heat (when drops freeze), stronger updrafts, & greater charge separation

Mutual Dependence between Thermodynamics and Aerosols

- Aerosols may influence how much of the CAPE is realized by an air parcel

Stolz et al. (2015) *J. Geophys. Res.*

Simultaneous Influences of Thermodynamics and Aerosols on Deep Convection and Lightning in the Tropics

2004 – 2011 TRMM Satellite Data

1. Total lightning flash density from LIS
2. Precipitation from PR
3. Convective feature (CF) database based on PR, LIS, …
4. Database uses ECMWF Reanalysis to provide T, p, water vapor → CAPE

GEOS-Chem model with TOMAS aerosol module

1. Lower troposphere aerosol number concentrations, N40, as CCN proxy
2. N40 = number concentration of aerosols with diameter > 40 nm
3. Use lowest 10 layers (to ~850 hPa) for N40 data

Coarse grid resolution (2.5°); 38°S – 38°N global study

Stolz et al. (2015) *J. Geophys. Res.*

Thermodynamic Variables Used in Analysis

CAPE = convective available potential energy

NCAPE = normalized CAPE

= mixed layer CAPE divided by depth of positive area of sounding

NCAPE = 0.1 J kg^{-1} m^{-1} could represent CAPE = 1000 J kg^{-1} over a 10 km depth

NCAPE as estimate for potential intensity of deep convection

LCL = lifting condensation level $= 0.12 \times (T_{sfc} - T_d)$

(surface T and dewpoint; 0.12 = 1 K/8.5 km scale height)

FH = freezing height

WCD = warm cloud depth = FH − LCL

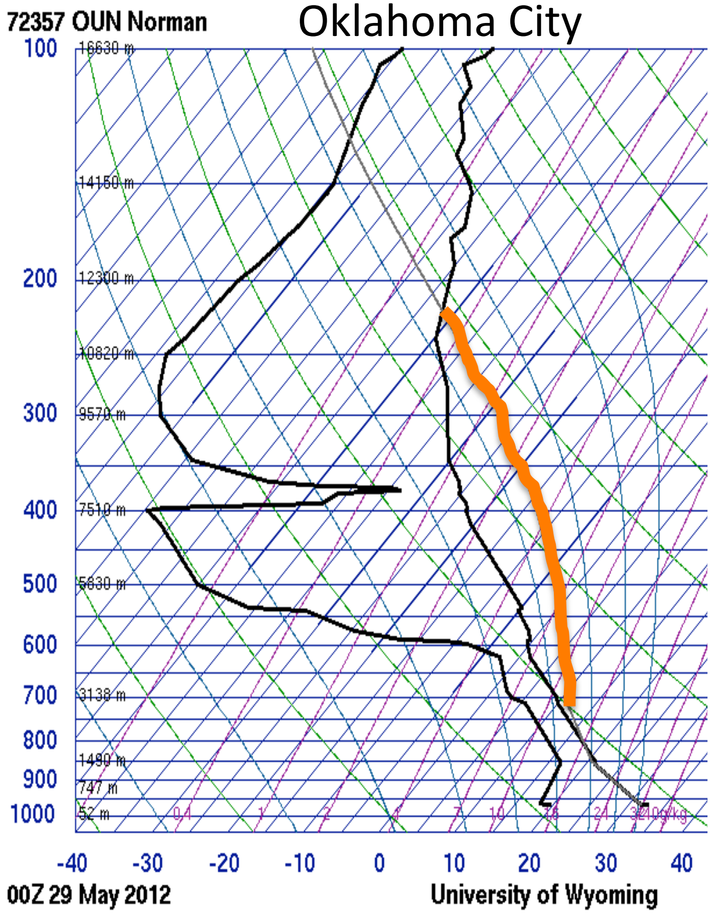
Stolz et al. (2015) *J. Geophys. Res.*

Midlatitudes versus Tropics

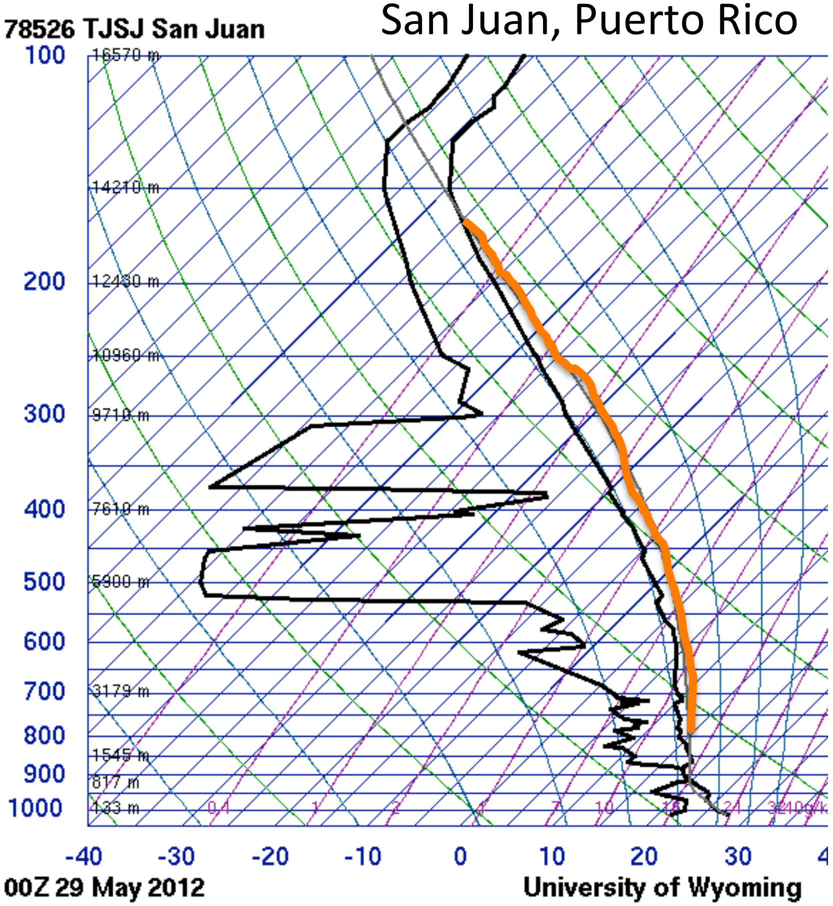
Same value of CAPE but one is short and fat and the other is long and skinny

→ Normalized CAPE accounts for these differences

Oklahoma City



San Juan, Puerto Rico



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FH = freezing height

WCD = warm cloud depth = FH − LCL

Stolz et al. (2015) *J. Geophys. Res.*

Storm Variables Used in Analysis

VPRR = vertical profile of radar reflectivity

AVGHT30 = average height of 30 dBZ echoes

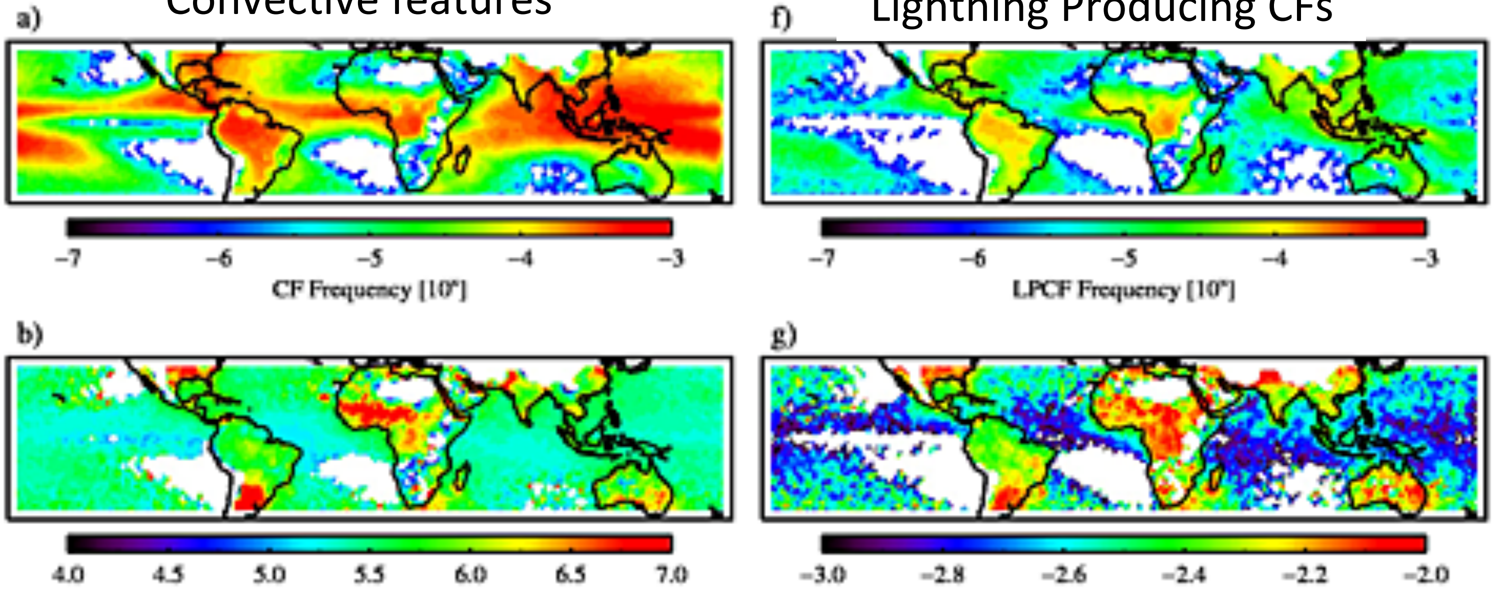
= peak altitude in the mean VPRR where the reflectivity was between 30.0 and 39.9 dBZ, relative to ground surface

TLD = total lightning density (flashes min^{-1})

= total lightning flash rate divided by area of convective feature

Stolz et al. (2015) *J. Geophys. Res.*

Global Statistics



Convective features

Lightning Producing CFs

Frequency

Avg Height of 30 dBZ

Flash Density

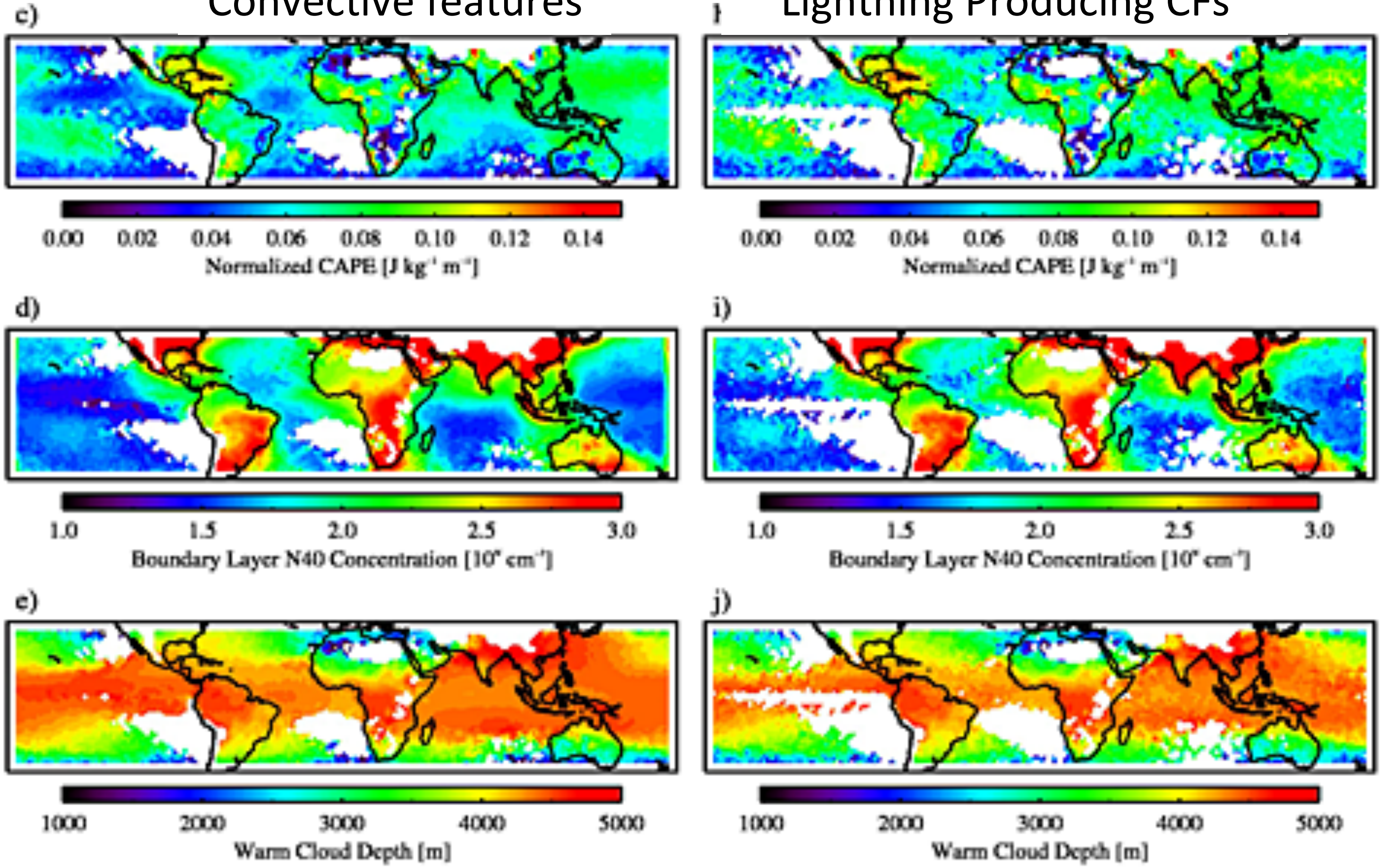
Similar pattern of 30 dBZ height and Flash Density for continents

Stolz et al. (2015) *J. Geophys. Res.*

Global Statistics

Convective features

Lightning Producing CFs



Normalized CAPE

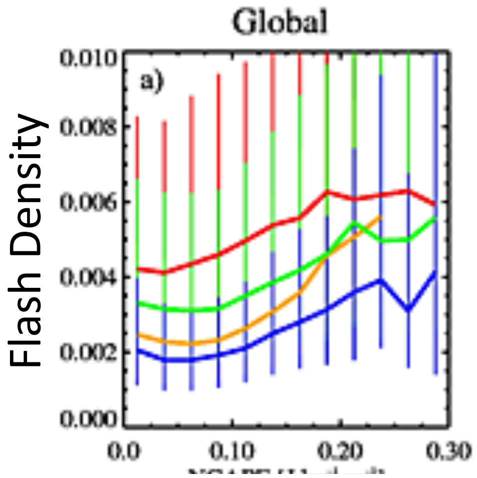
PBL N40 Concentration

Warm Cloud Depth

- Similar NCAPE for oceans and continents
- Different N40 for ocean and continents
- Similar WCD for ocean and continents

Stolz et al. (2015) *J. Geophys. Res.*

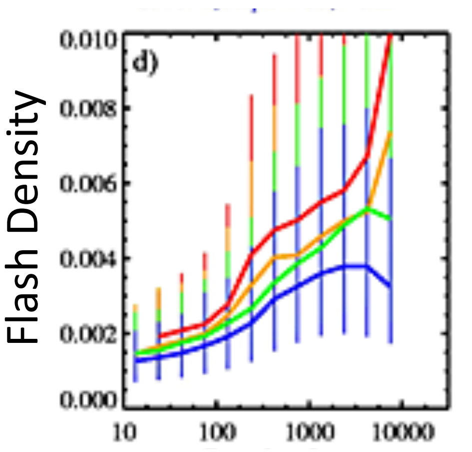
Sensitivity of Lightning to Thermodynamics and Aerosols



Normalized CAPE

High N40, shallow WCD
Low N40, shallow WCD
High N40, deep WCD
Low N40, deep WCD

- Flash density variability greater with respect to N40 than NCAPE for continents



Aerosol Concentration in PBL

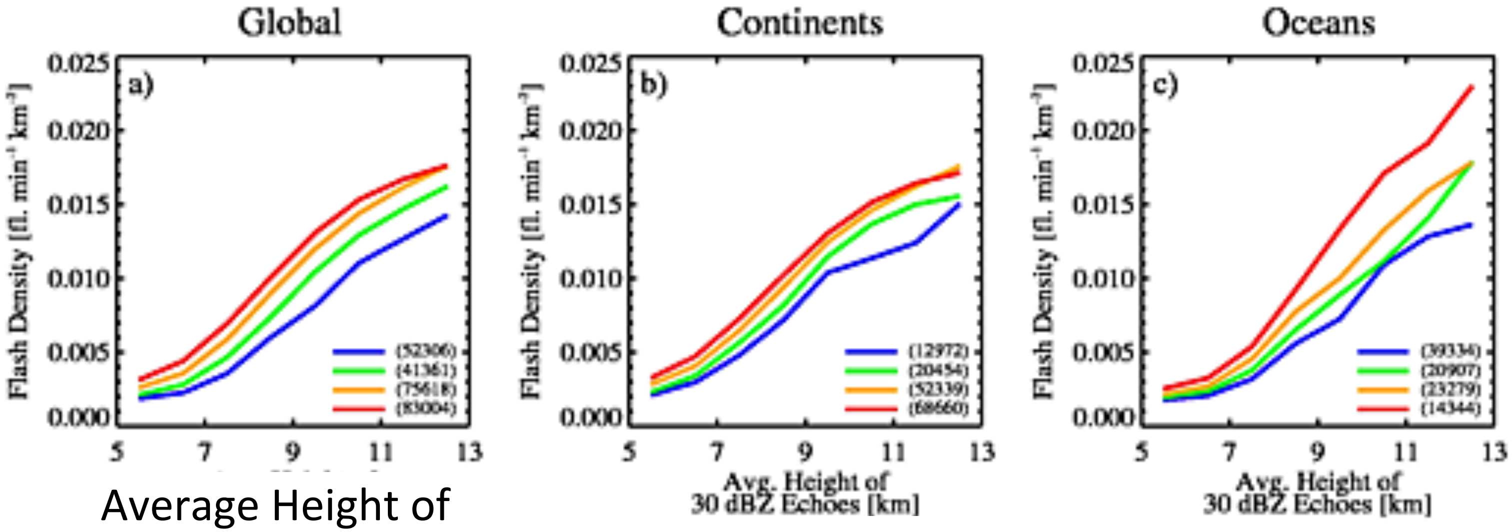
High NCAPE, shallow WCD
Low NCAPE, shallow WCD
High NCAPE, deep WCD
Low NCAPE, deep WCD

Stolz et al. (2015) *J. Geophys. Res.*

Variations with Warm Cloud Depth

- As N40 increases, both total flash density and average height of 30 dBZ echoes increase

Flash Density



Average Height of 30 dBZ Echoes

N40 > 500 cm^{-3}

200 < N40 < 500

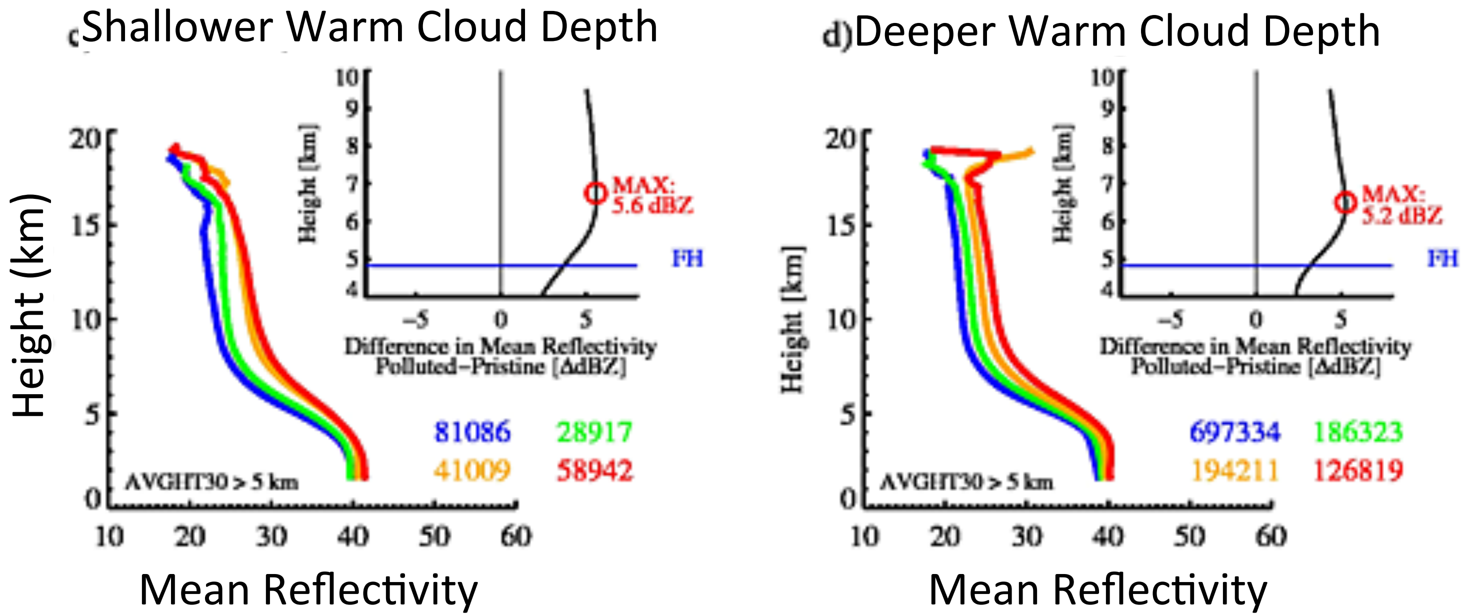
100 < N40 < 200

N40 < 100

Stolz et al. (2015) *J. Geophys. Res.*

Variations with Warm Cloud Depth

- Vertical profiles of radar reflectivity show at a given altitude increases in radar reflectivity as N40 increases
- Largest changes are for shallower WCD
- Behavior is consistent with aerosols invigorating storms via latent heating



c) Shallower Warm Cloud Depth

d) Deeper Warm Cloud Depth

N40 > 500 cm^{-3}

200 < N40 < 500

100 < N40 < 200

N40 < 100

Stolz et al. (2015) *J. Geophys. Res.*

Aerosol Effects on Flash Rate

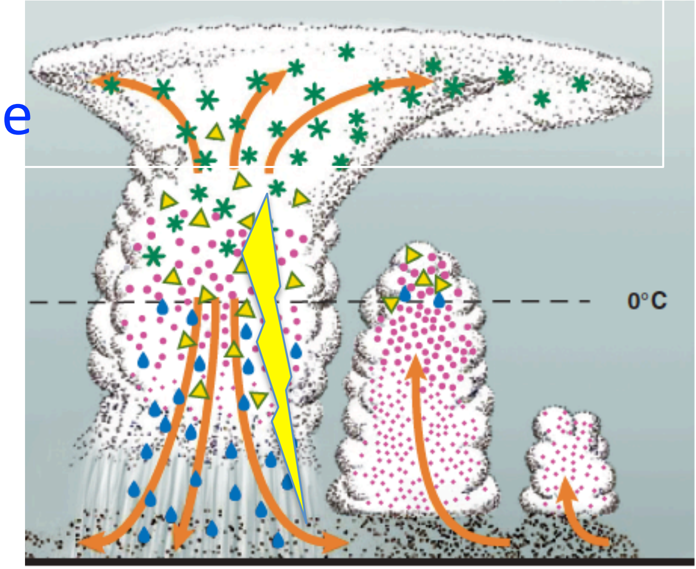
- Highest flash rate density and 30 dBZ heights associated with deep convective features that develop in polluted environments
  - shallower warm cloud depths
  - normalized CAPE > 0.25 J kg^{-1} m^{-1}

- Merged or Simultaneous Hypothesis: aerosols and thermodynamics combine to affect lightning

Stolz et al. (2015) *J. Geophys. Res.*

Find Warm Cloud Depth Matters

- Very shallow warm cloud depths
  - ➢ aerosol effect on cloud droplets do not have enough time to affect collision/coalescence processes
- Shallow warm cloud depths
  - ➢ more cloud drops reach the mixed phase region allowing aerosols to affect riming, charge separation, and lightning flash rates
- Deep warm cloud depths
  - ➢ cloud drops do not reach mixed phase region because they have already converted to precipitation via collision/coalescence processes



Stolz et al. (2015) *J. Geophys. Res.*

Summary

- Observational evidence of aerosols affecting lightning flash rate
    - Possible weekly cycle of lightning with peak middle of week after aerosol concentrations increase
- Modeling evidence of aerosols affecting lightning flash rate
    - more cloud drops reach the mixed phase region allowing aerosols to affect riming, charge separation, and lightning flash rates
- Analysis of primarily tropical convection
    - Highest flash rates associated with polluted environments with shallower warm cloud depths and high normalized CAPE