Aerosols and Meteorology

1) Background

2) Aerosols and precipitation

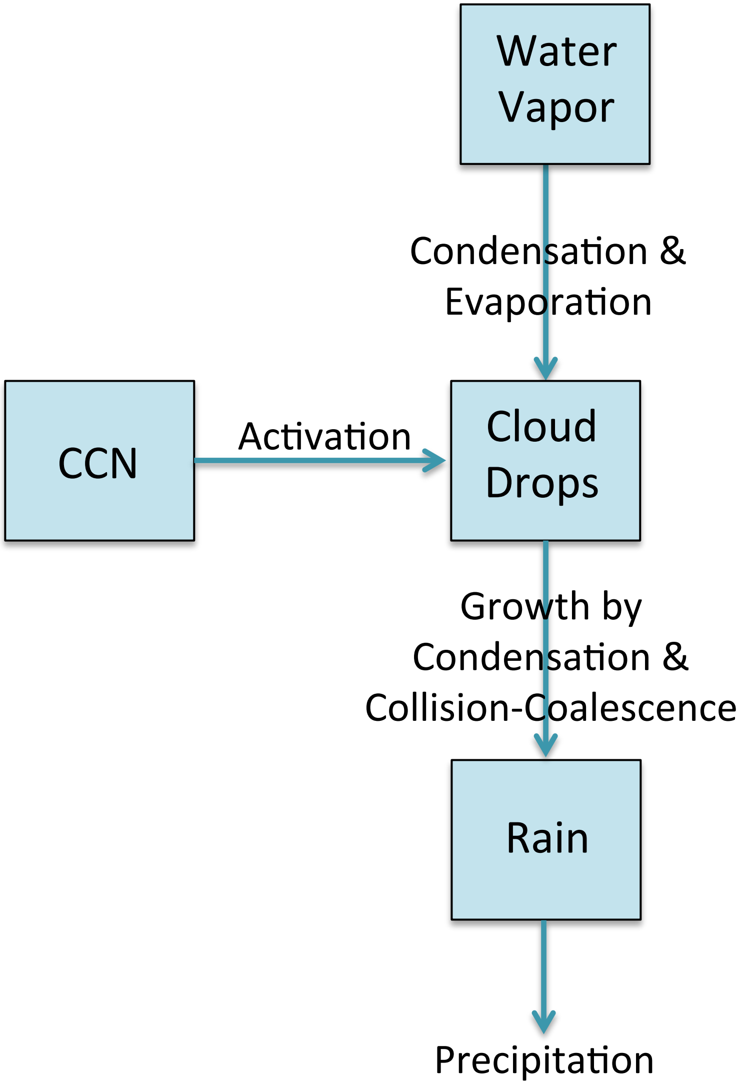
3) Aerosol effects on lightning

4) Smoke and severe storms

Lecture 2: Aerosols and Precipitation

- Summarize Tao et al. (2012) *Rev. Geophys.* article
- Present Some Cloud Resolving Model (CRM) Results
  - Teller and Levin (2006);
  - van den Heever and Cotton (2007);
  - Tao et al. (2012);
- Idealized Simulations vs “Real” Meteorology
  - Eidhammer et al (2014);
  - Sarangi et al (2015)

Review: Warm Rain Formation

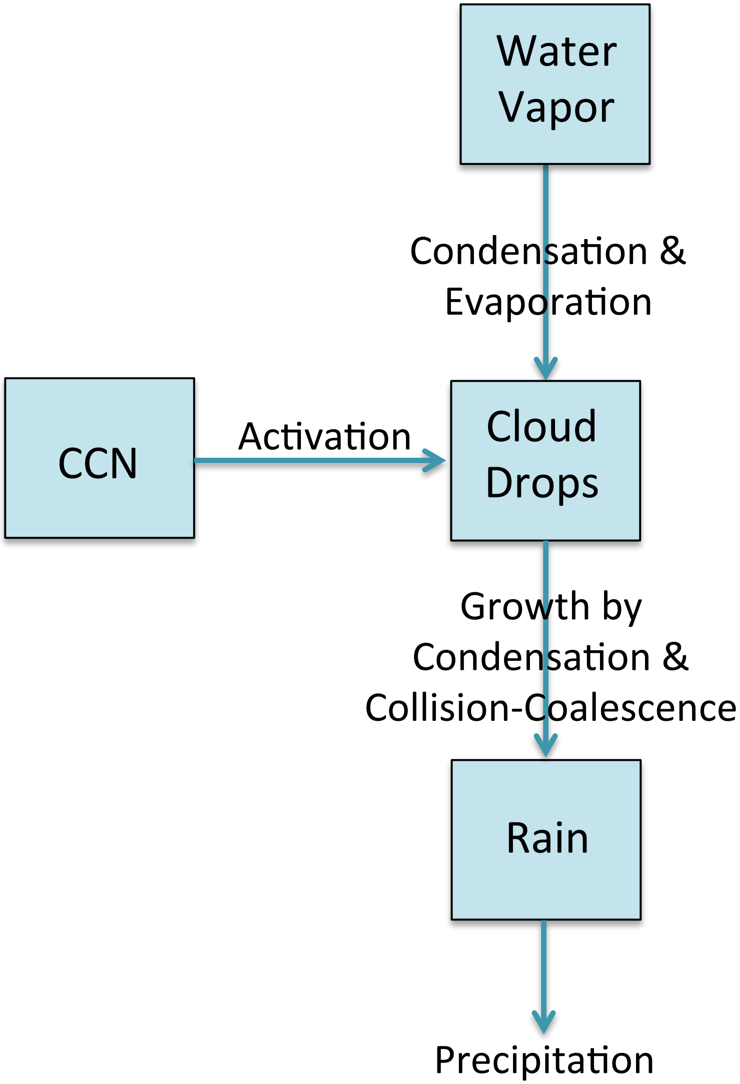


Rain formed by

- growing cloud drops,
- collision-coalescence of cloud drops,
- collection of cloud drops by rain drops

CCN = cloud condensation nuclei

Warm Rain Formation



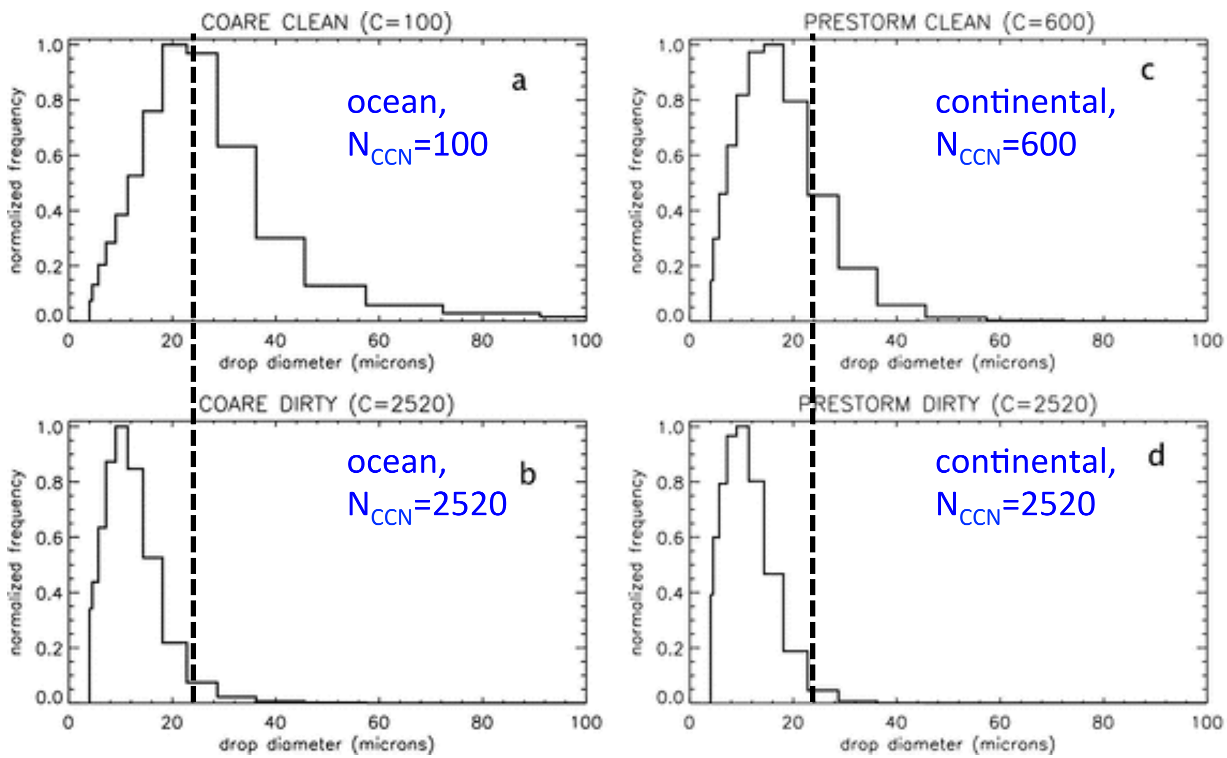
- When N_{CCN} increase, N_{drop} increase
- Higher N_{drop} leads to smaller cloud drops → collision-coalescence becomes less efficient → difficult to form rain (i.e., drops > 24 µm diameter)
- Higher N_{drop} leads to narrow cloud drop size spectrum → less difference in fall speeds leads to suppression of rain

CCN = cloud condensation nuclei
NCCN = number of CCN
Nd = number of cloud drops

Warm Rain Formation

- When N_{CCN} increase, N_{drop} increase
- Higher N_{drop} leads to smaller cloud drops → collision-coalescence becomes less efficient → difficult to form rain (i.e., drops > 24 μm diameter)
- **Higher N_{drop} leads to narrow cloud drop size spectrum** → less difference in fall speeds leads to **suppression of rain**

Compare drop size distributions in top panel to bottom panel



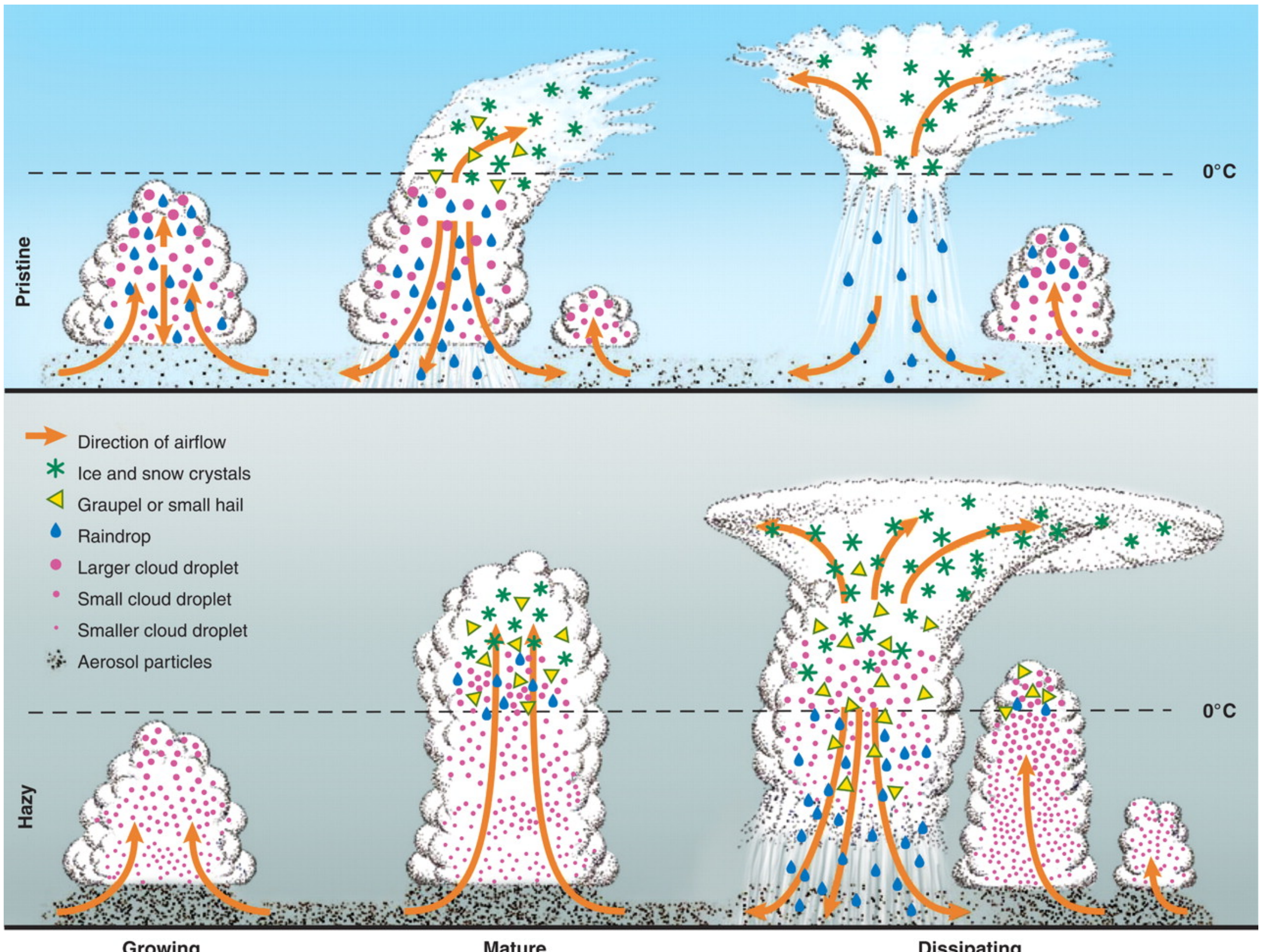
Tao et al. (2012) *Rev. Geophys.*

Convective Clouds with Ice Phase

Increased number of aerosols with same liquid water content lofts cloud drops to mixed phase region,
→ invigorates storms

Low aerosol number concentrations

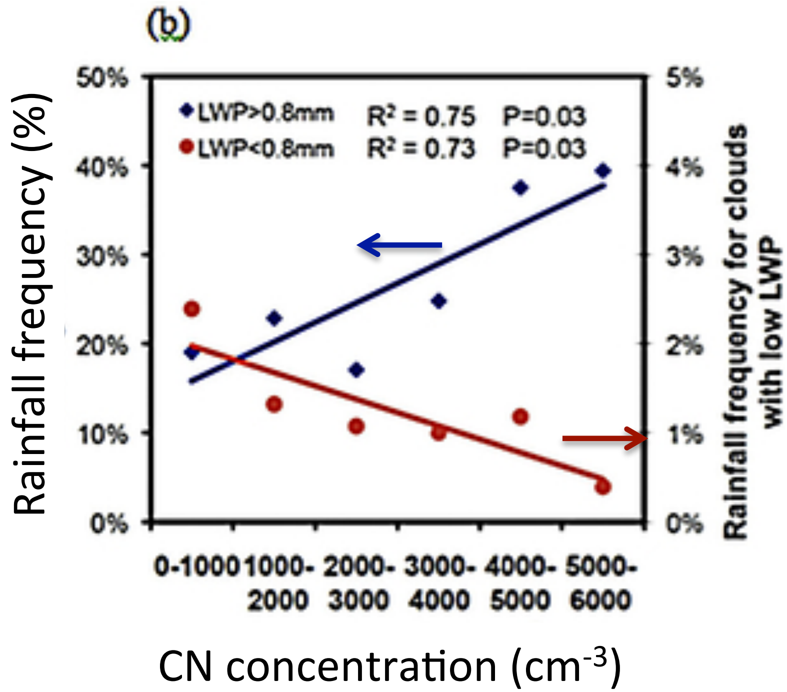
High aerosol number concentrations



Rosenfeld et al. (2008) *Science*

Evidence of Aerosol Invigoration Effect

10 years of data from DOE ARM Southern Great Plains site



- As CN increases frequency of rainfall increases when LWP > 0.8 mm
- As CN increases frequency of rainfall decreases when LWP < 0.8 mm

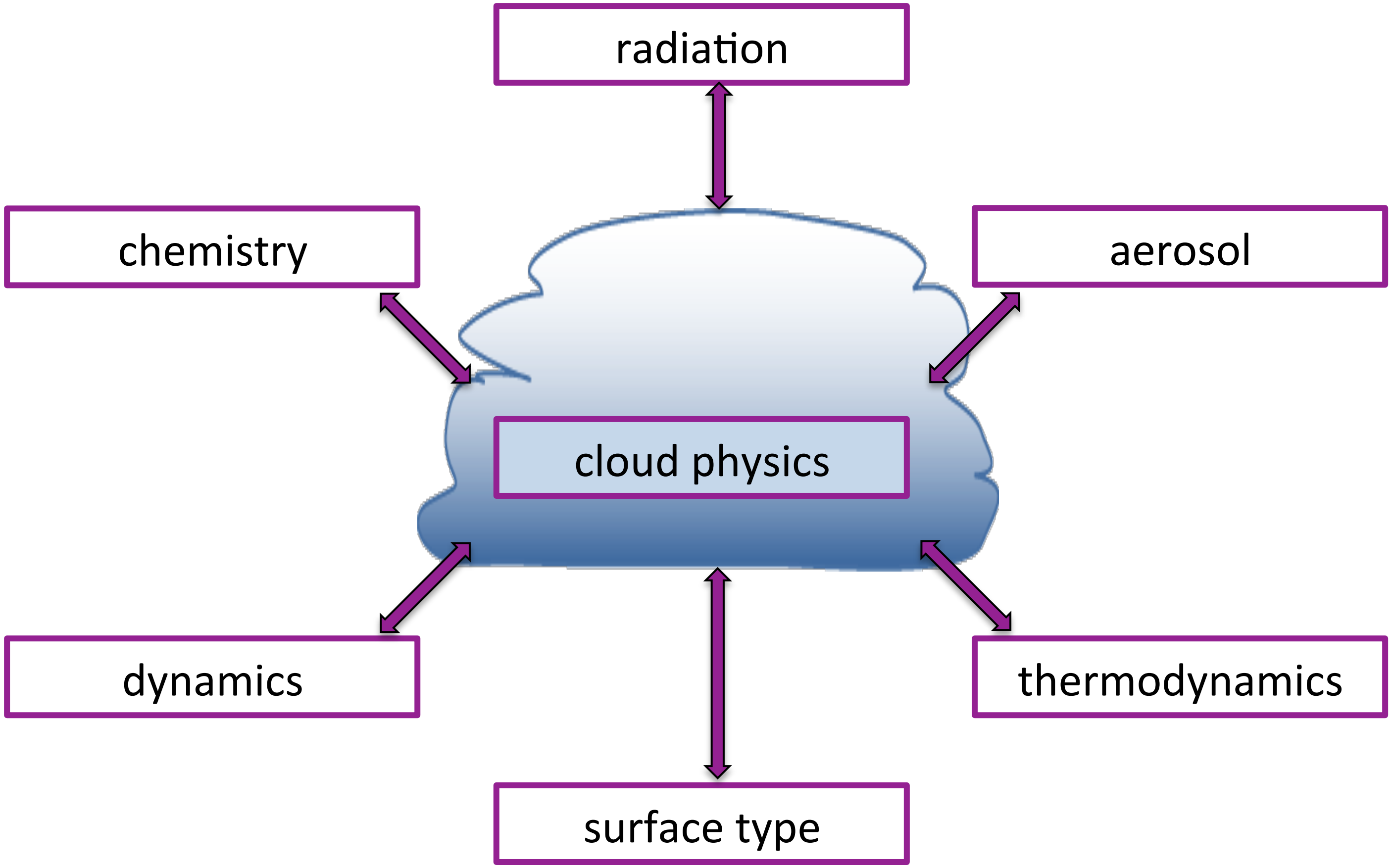
10 years of data from DOE ARM Southern Great Plains site

CN = condensation nuclei
= aerosol concentration
LWP = liquid water path

Li et al. (2011) *Nature Geosci.*

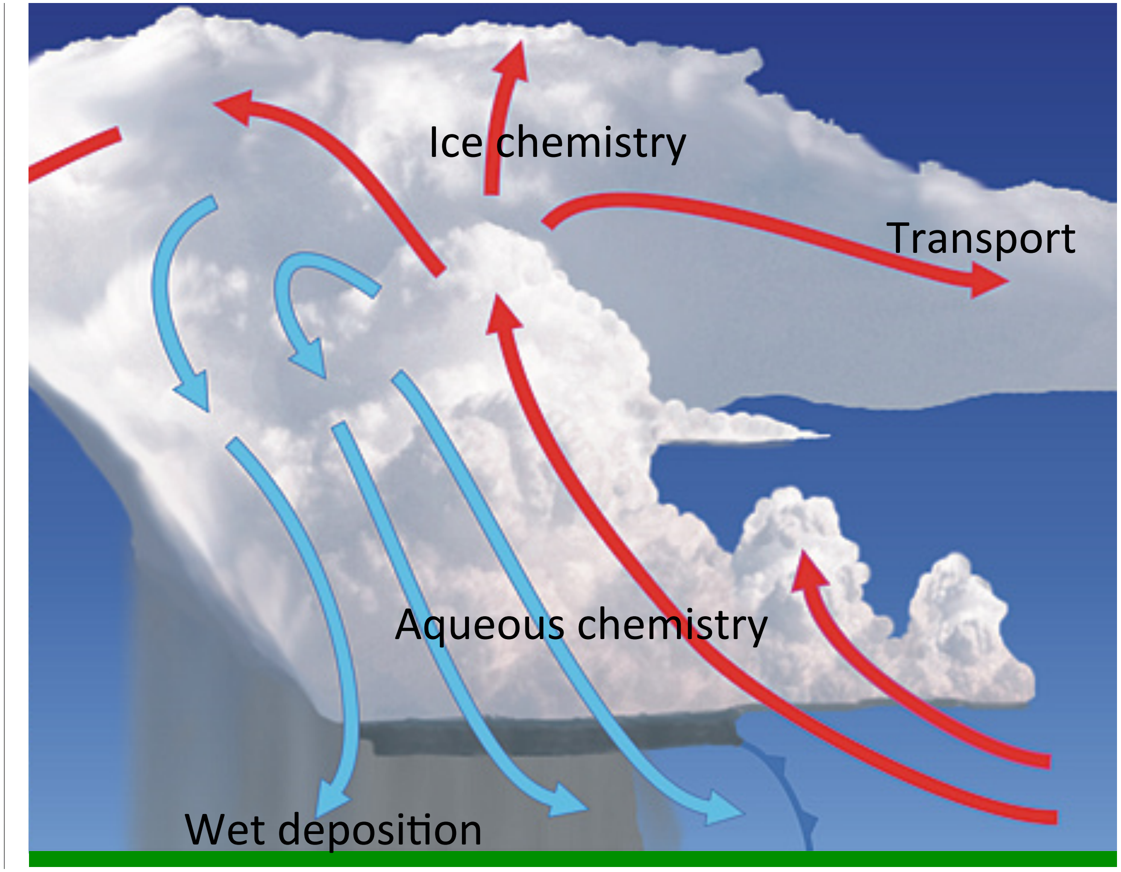
Modeling Aerosol Effects on Clouds and Precipitation

Complex System



From Levin and Cotton, 2006

Cloud Effects on Aerosols



Aerosol growth via cloud chemistry

Aerosol removal in precipitation

Barth et al. (2011) *DC3 Science Plan*

Two-moment bulk scheme

Two moments are number and mass

That is, predict N and M of aerosols and cloud particles

Have up to 3 aerosol categories:
CCN = cloud condensation nuclei that activate into cloud drops
GCCN = giant CCN, usually sea salt, that activate into rain drops
IN = ice nuclei that nucleate into ice crystals

Usually 5 cloud particle categories:
Cloud drops
Rain
Ice crystals
Snow
Graupel or Hail

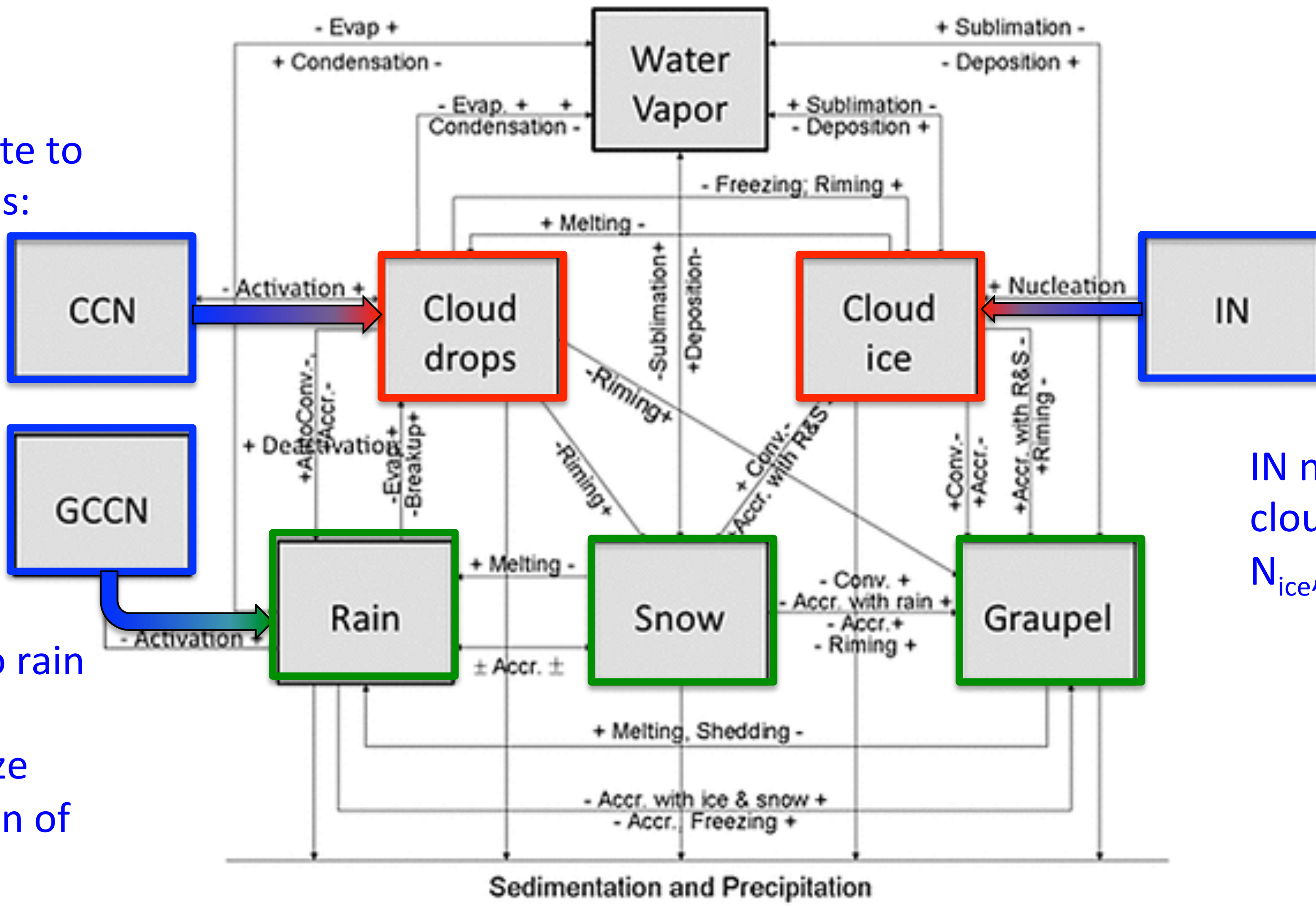
Graupel and Hail

Graupel is a supercooled droplets of water are collected and freeze on falling snowflakes. Snow pellets are graupel.

Hail is solid precipitation, water ice. It has layers of water (from liquid drops and vapor) as its structure.

Aerosols and Cloud Particle Processes for a Two-moment Bulk Scheme (Predict N and M)

CCN activate to cloud drops: N_d, q_c



IN nucleate to cloud ice: N_{ice}, q_{ice}

Giant CCN activate to rain drops: N_r from size distribution of q_r

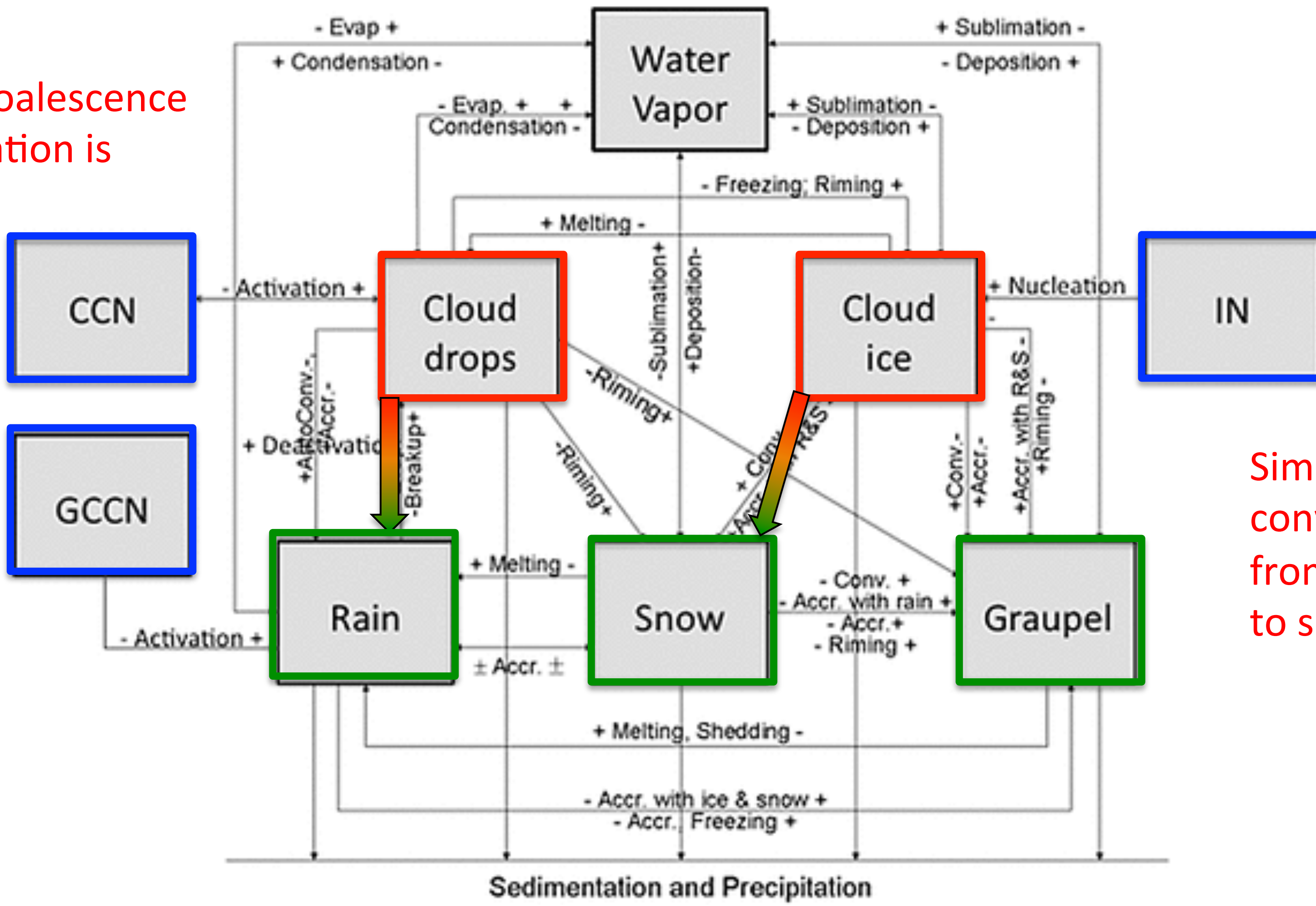
N = number
M = mass
CCN = cloud condensation nuclei
q = mass mixing ratio

Aerosols **Non-precipitating cloud hydrometeors**
Precipitating cloud hydrometeors

Predict N and M of aerosols and cloud particles

Two-moment bulk scheme

Collision-coalescence representation is important!



Similar conversion from cloud ice to snow

N = number
M = mass
CCN = cloud condensation nuclei
q = mass mixing ratio

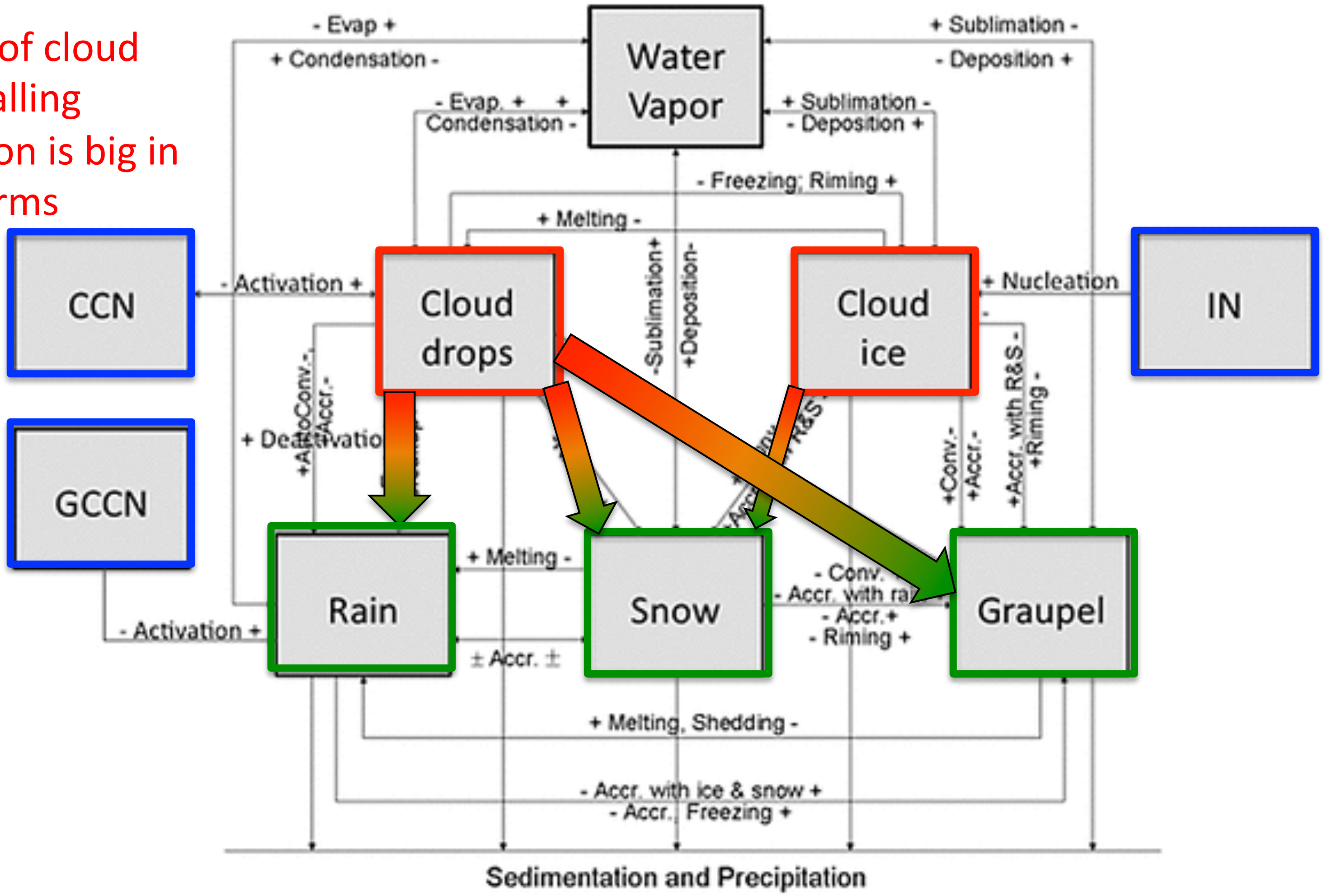
Aerosols **Non-precipitating cloud hydrometeors**

Precipitating cloud hydrometeors

Predict N and M of aerosols and cloud particles

Two-moment bulk scheme

Collection of cloud drops by falling precipitation is big in severe storms



Aerosols **Non-precipitating cloud hydrometeors**

Precipitating cloud hydrometeors

N = number

M = mass

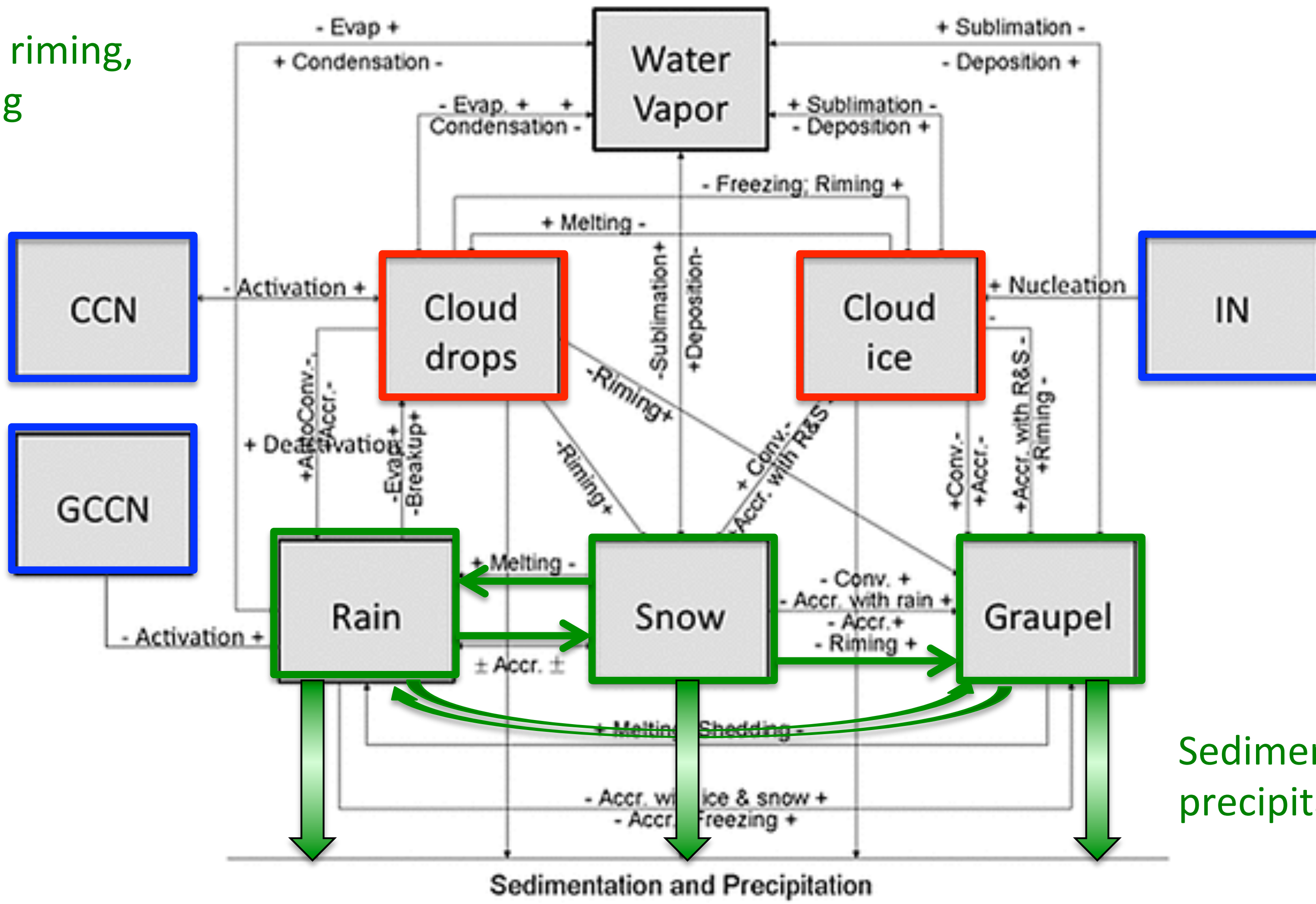
CCN = cloud condensation nuclei

q = mass mixing ratio

Predict N and M of aerosols and cloud particles

Two-moment bulk scheme

Collection, riming, and melting



Sedimentation and precipitation

N = number
M = mass
CCN = cloud condensation nuclei
q = mass mixing ratio

Aerosols **Non-precipitating cloud hydrometeors**
Precipitating cloud hydrometeors

Aerosol Effects on Precipitation

Results from Modeling Studies

- Reisin et al. (1996a,b) *J. Atmos. Sci.*
  - 2-D axisymmetrical cloud model with spectral bin cloud physics
  - Polluted clouds produce less precipitation
- Khain et al. (2005) *QJRMS*; Zhang et al. (2005) *JGR*
  - Smaller cloud droplets lofted to mixed phase region, freezing released latent heating, invigorating convection
  - No squall line at low N_{CCN}, but did produced squall line for high N_{CCN}
- Seifert and Beheng (2005) *Meteor. Atmos. Phys.*
  - Aerosol effects on convection depend on cloud type
  - Small convection → decreased precipitation and w_{max}
  - Multi-cell storms → secondary convection promoted, increasing w_{max} and precipitation
  - Supercell storms → least sensitive to CCN increases
  - Importance of latent heat of freezing on storm

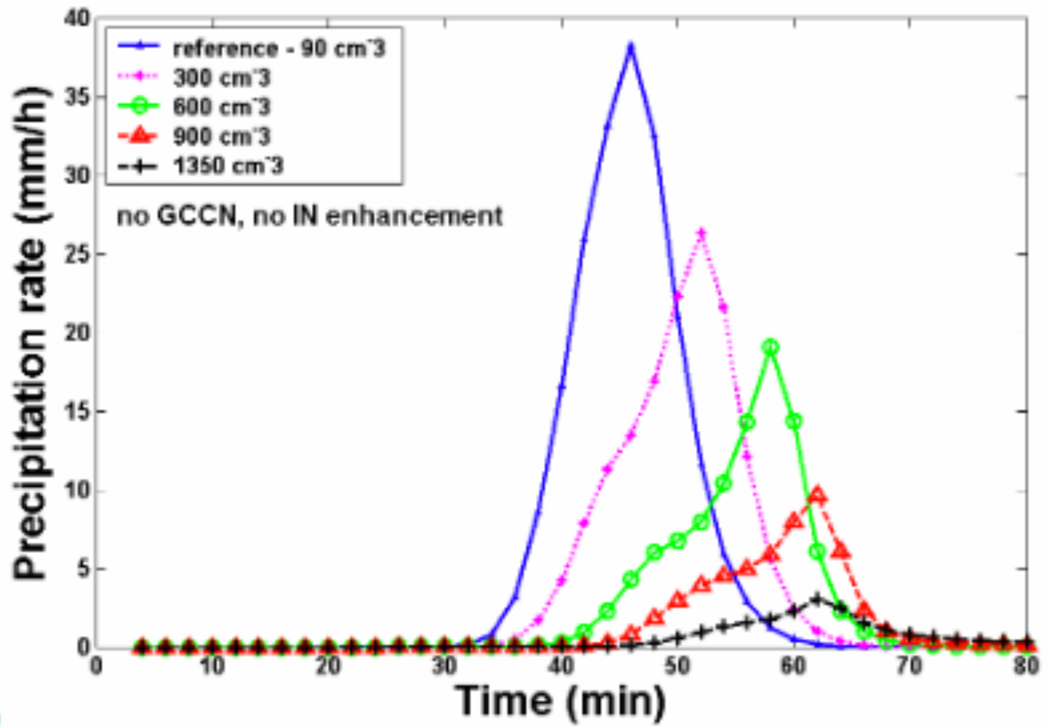
Results from Modeling Studies

Teller and Levin (2006) *Atmos. Chem. Phys.*

2-D cloud model with spectral bin cloud physics

Polluted clouds produce less precipitation, initiation of precipitation is delayed and lifetime of clouds is longer

Precipitation rate as a function of time



Teller and Levin (2006) *Atmos. Chem. Phys.*

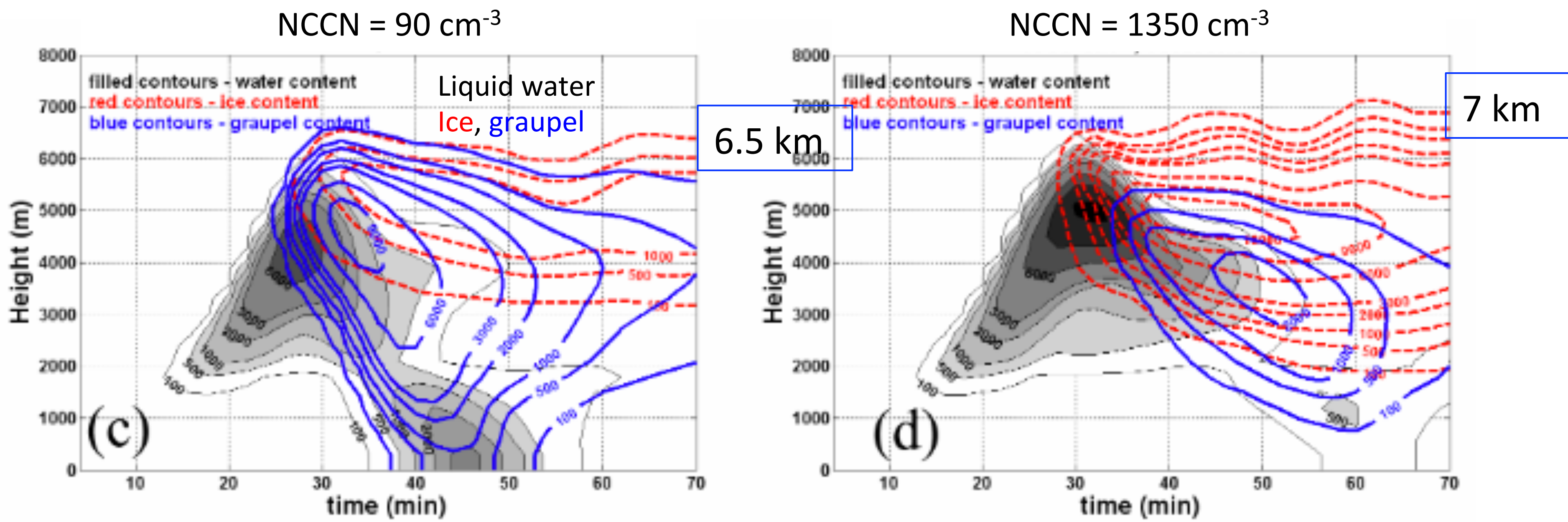
Results from Teller and Levin (2006)

Polluted clouds produce less precipitation, initiation of precipitation is delayed and lifetime of clouds is longer

Polluted clouds have higher cloud tops than clean clouds

(in agreement with aerosols invigorating storms)

Vertical cross sections of water, ice, and graupel horizontally integrated as a function of time



Teller and Levin (2006) *Atmos. Chem. Phys.*

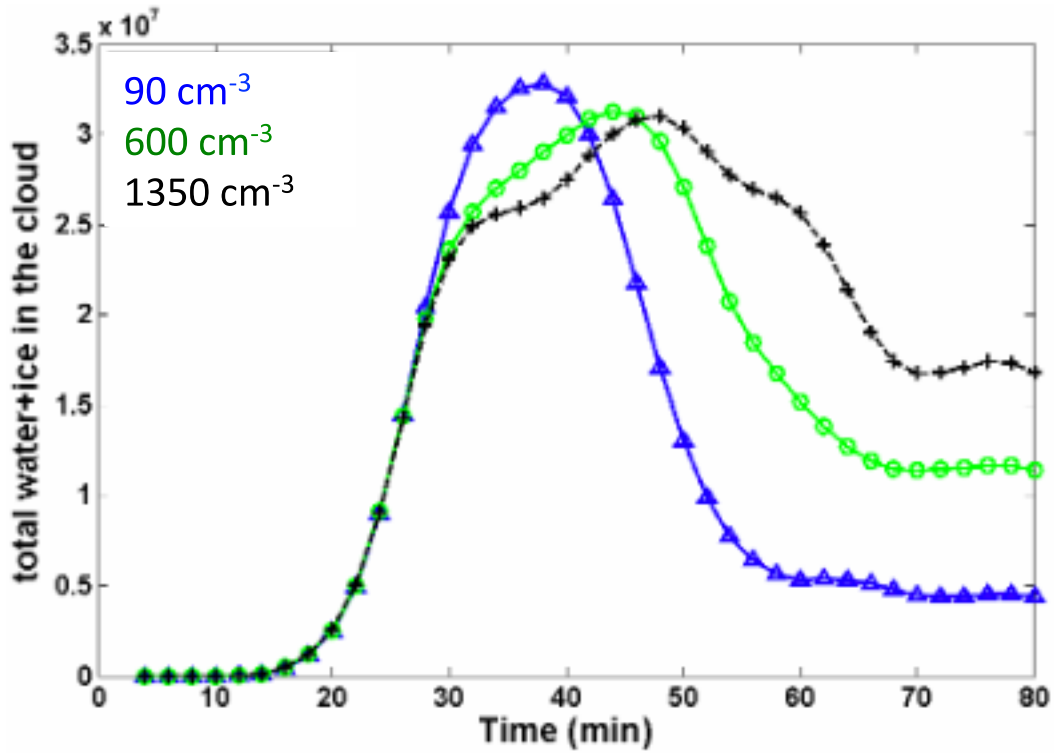
Results from Teller and Levin (2006)

Polluted clouds produce less precipitation, initiation of precipitation is delayed and lifetime of clouds is longer

Polluted clouds have higher cloud tops than clean clouds

More water vapor transported to mid troposphere in polluted conditions

Total condensed water mass in atmosphere as a function of time



Teller and Levin (2006) *Atmos. Chem. Phys.*

Results from Teller and Levin (2006)

Polluted clouds produce less precipitation, initiation of precipitation is delayed and lifetime of clouds is longer

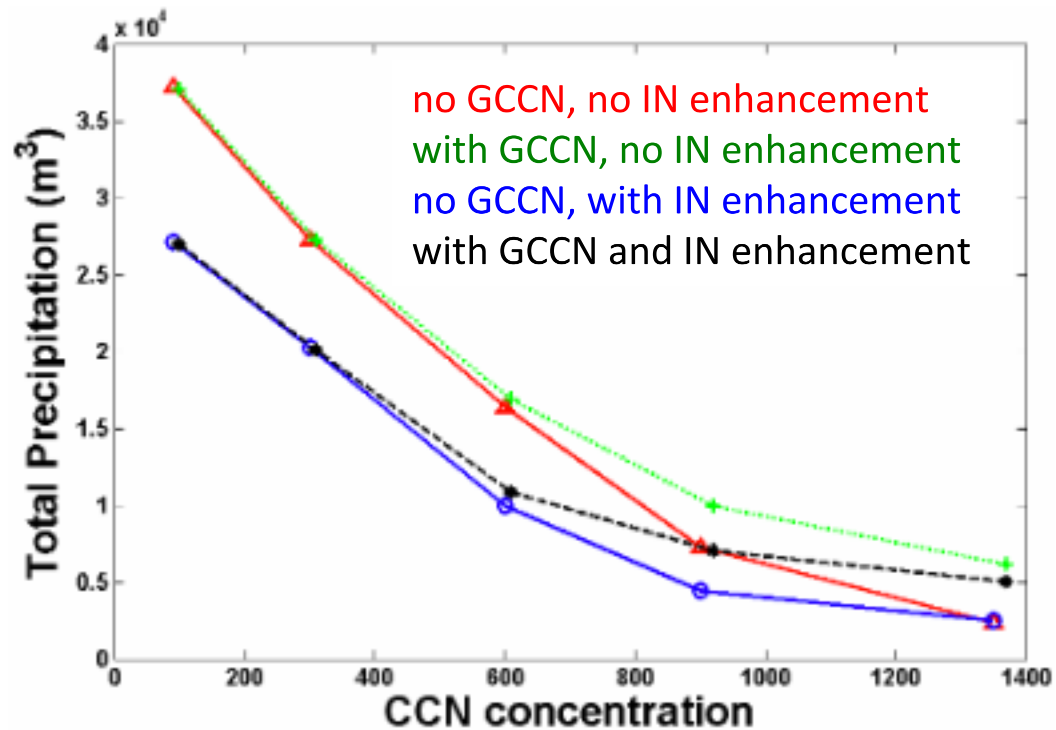
Polluted clouds have higher cloud tops than clean clouds

More water vapor transported to mid troposphere in polluted conditions

GCCN and IN affect amount of precipitation, cloud size, etc

(GCCN = giant CCN, IN = ice nuclei)

Total precipitation at ground as a function of CCN concentration



Teller and Levin (2006) *Atmos. Chem. Phys.*

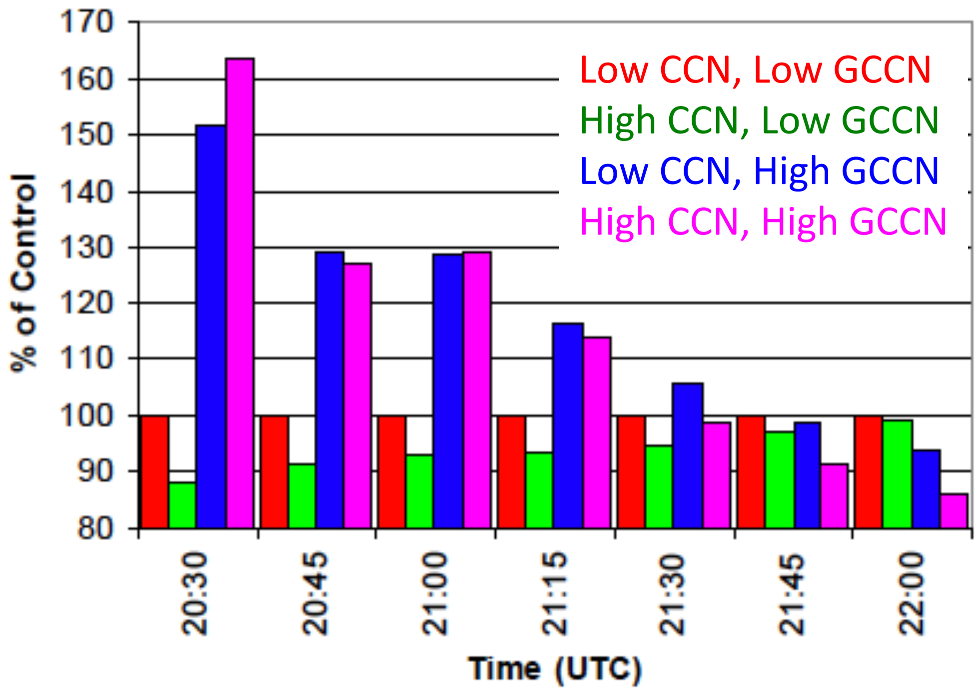
Results from Modeling Studies

Van den Heever et al. (2006); van den Heever and Cotton (2007)

3-D RAMS cloud model with two-moment cloud physics and lookup tables for cloud drop activation

Variations in aerosol concentration affect both physical and dynamical characteristics of storms

Percent Change in Total Precipitation between simulations with different CCN concentrations as a function of time from simulations over St. Louis, MO



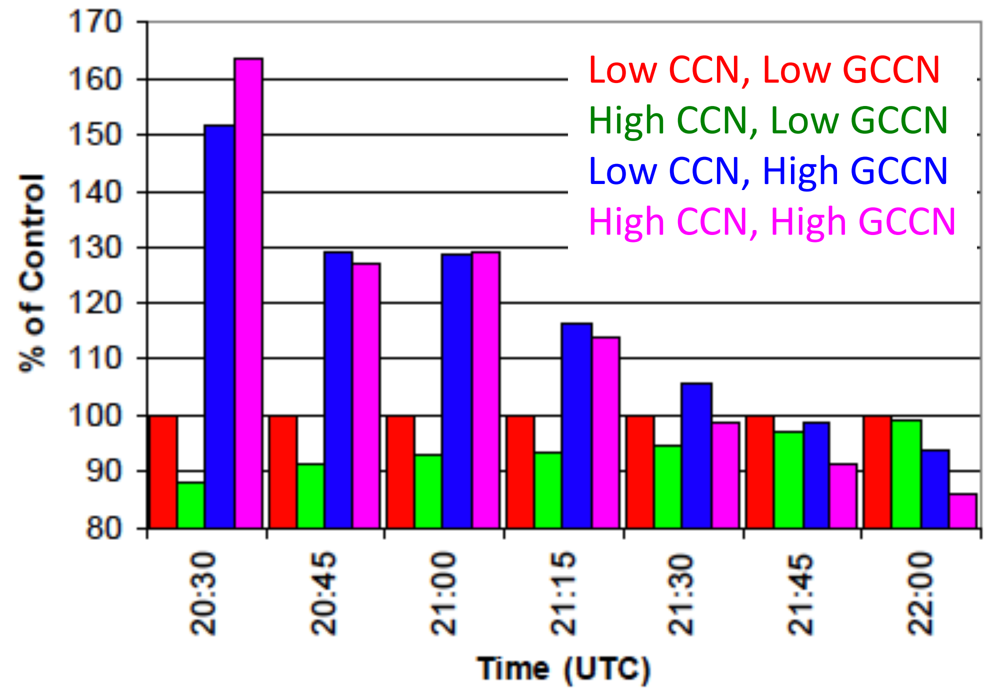
https://ams.confex.com/ams/Madison2006/webprogram/Paper112258.html

Results from van den Heever and Cotton (2007)

Variations in aerosol concentration affect both physical and dynamical characteristics of storms

Venting of aerosols actually cleans lower atmosphere consequently changing inflow aerosol concentrations

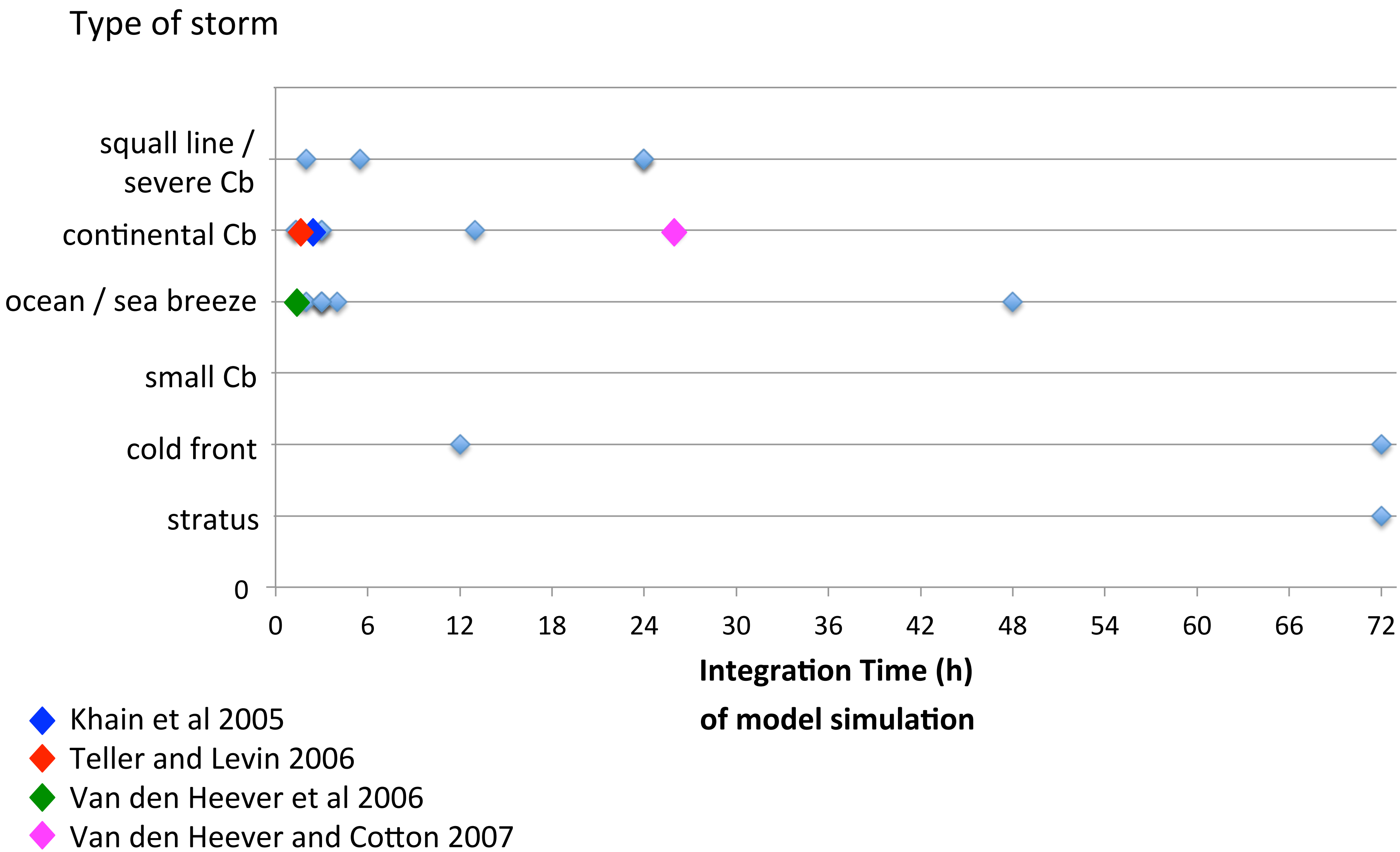
Cold pools differ substantially between simulations altering storm dynamics



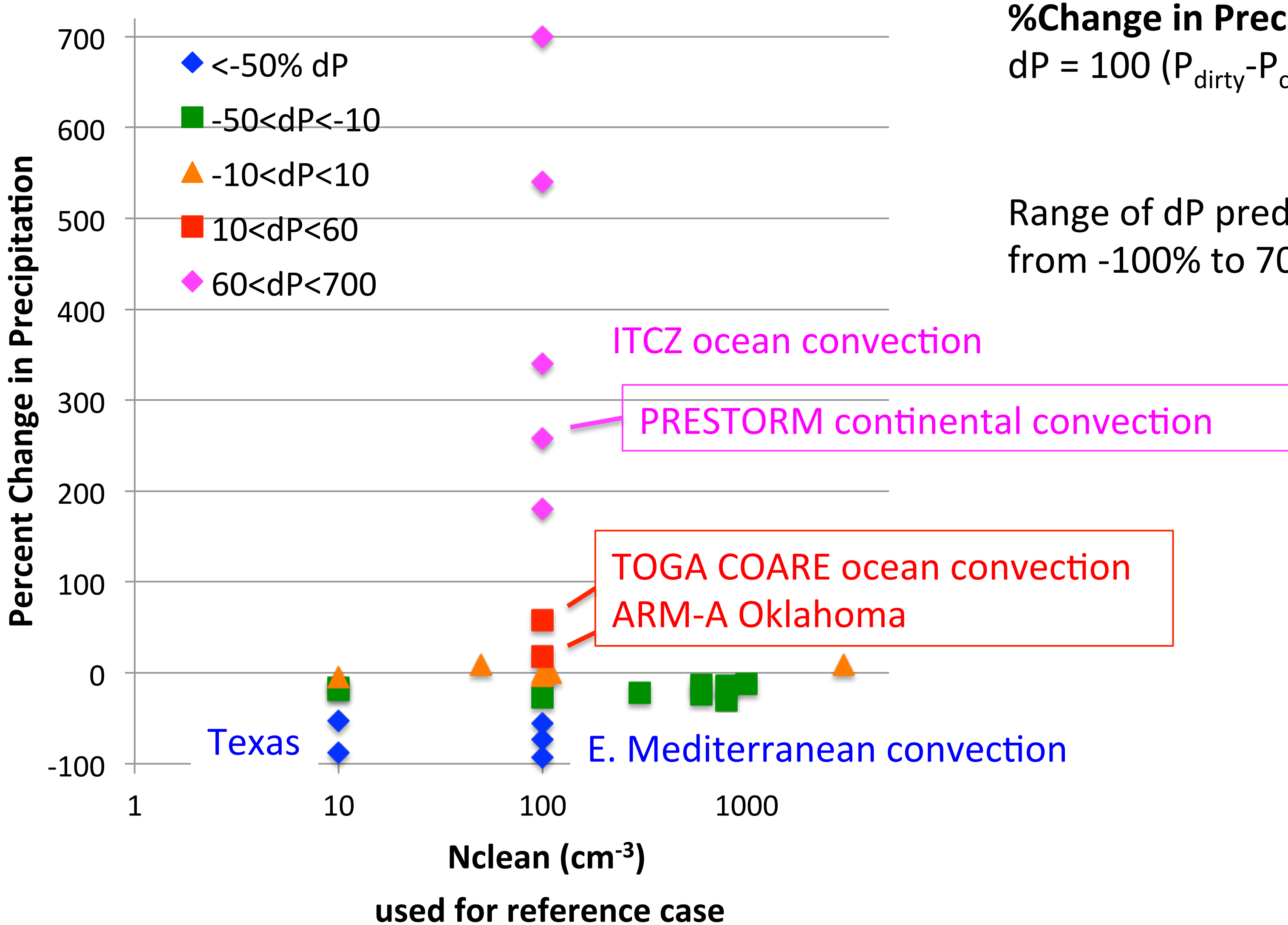
Percent Change in Total Precipitation between simulations with different CCN concentrations as a function of time from simulations over St. Louis, MO

Van den Heever et al. (2006) *J. Atmos. Sci.*
Van den Heever and Cotton (2007) *J. Appl. Meteor.*

Tao et al. (2012) list 22 Studies from 2004-2011



27 Simulation Sensitivity Cases Reported in Tao et al. (2012)



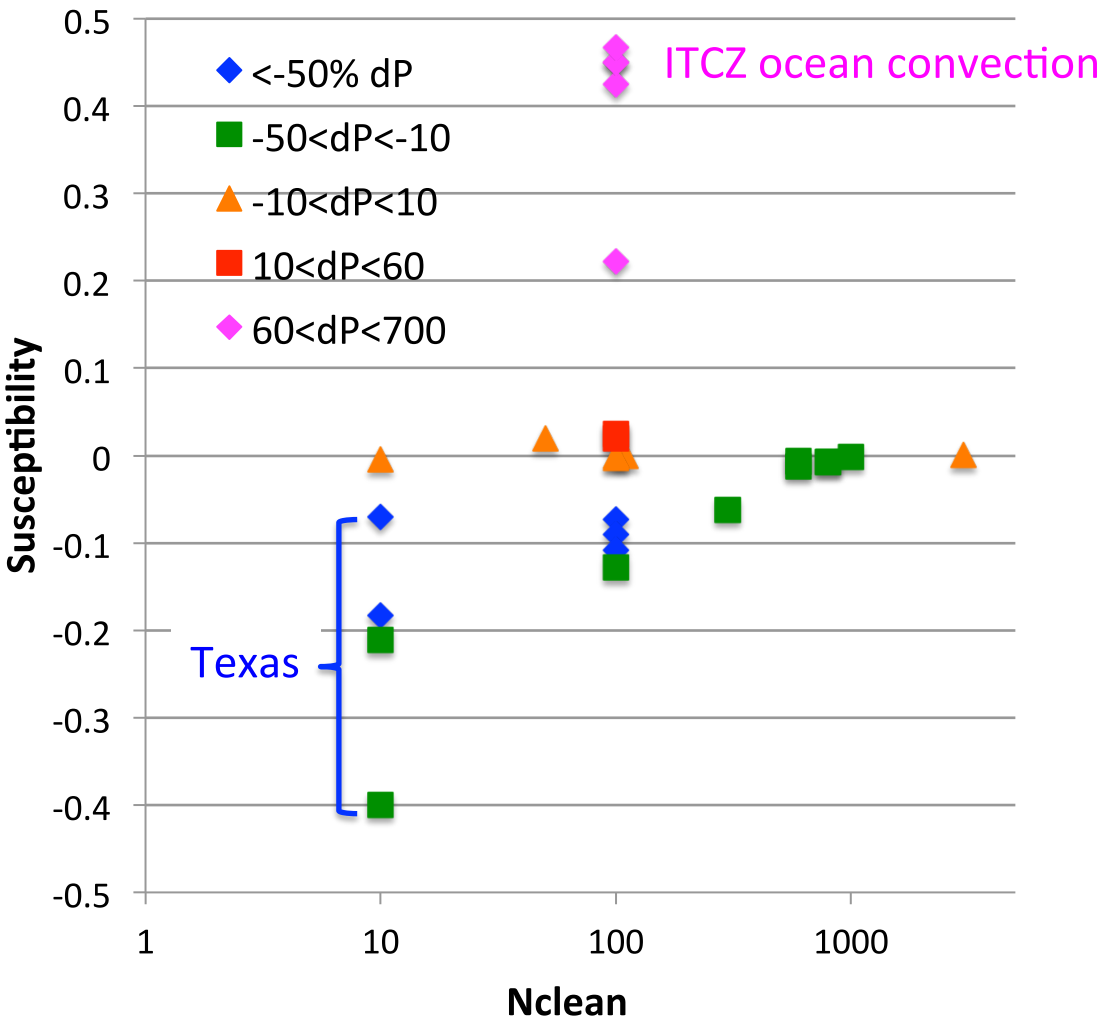
%Change in Precipitation

$dP = 100\,(P_{dirty} - P_{clean})/P_{clean}$

Range of dP predictions are from -100% to 700%

From Table 4, Tao et al. (2012) *Rev. Geophys.*

Susceptibility of Convective Storms to Aerosols



Susceptibility = $\frac{dP}{dN}$

No obvious reason why some simulations predict more precipitation and others predict less precipitation

Factors:

Early stages of storm often dominated by microphyscial processes → less rain

→ Length of integration possibly important

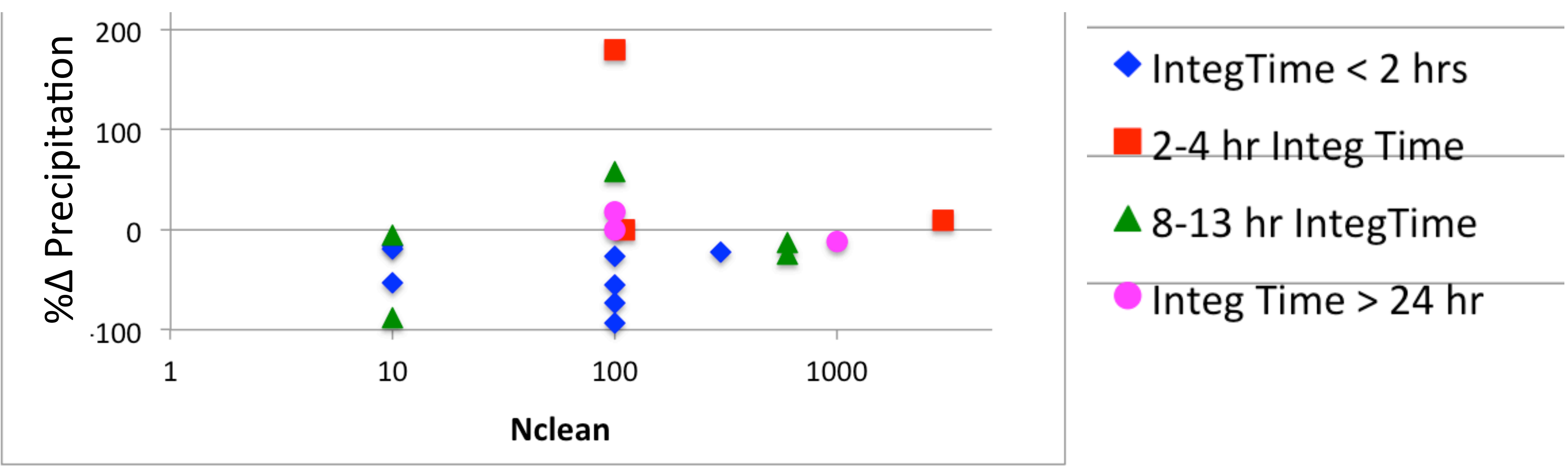
Relative Humidity
Cloud Type
Wind Shear

From Table 4, Tao et al. (2012) *Rev. Geophys.*

Factors Causing Differences Among Model Studies

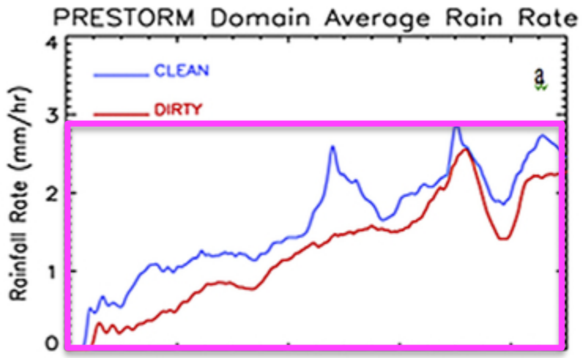
- Early stages of storm often dominated by microphysical processes → less rain
  →Length of integration possibly important

- All of the simulations integrating for ≤ 2 hours conclude precipitation is reduced

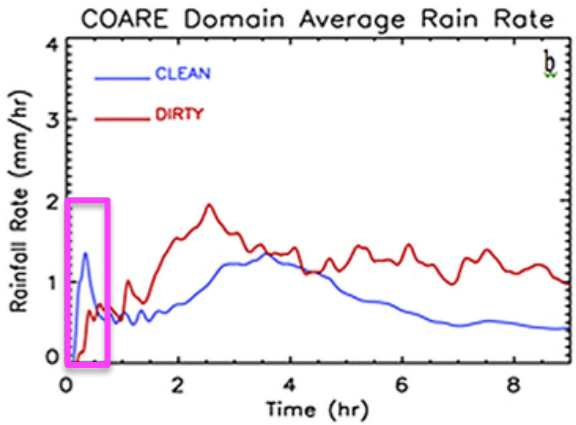


Tao et al. (2012) *Rev. Geophys.*

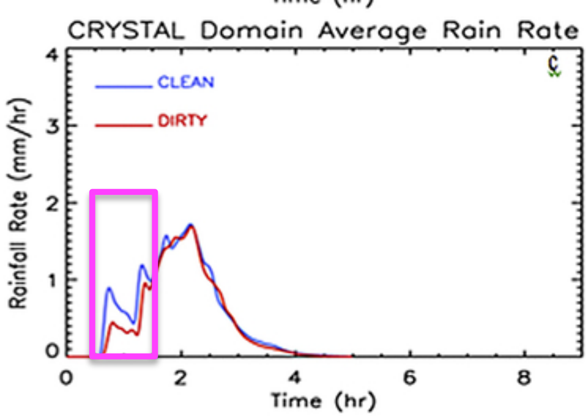
Early stage of storm has less rain under high CCN conditions



Oklahoma-Kansas
Nclean = 600
Ndirty = 1900



Oceanic (TWP)
Nclean = 100
Ndirty = 2400



Florida
Nclean = 600
Ndirty = 1900

Precipitation rate as a function of time for 3 storms

For TWP and Florida, precipitation reduced during first 30-60 minutes of storm

Tao et al. (2007) *J. Geophys. Res.*

Factors Causing Differences Among Model Studies

- Early stages of storm often dominated by microphysical processes → less rain
  →Length of integration possibly important

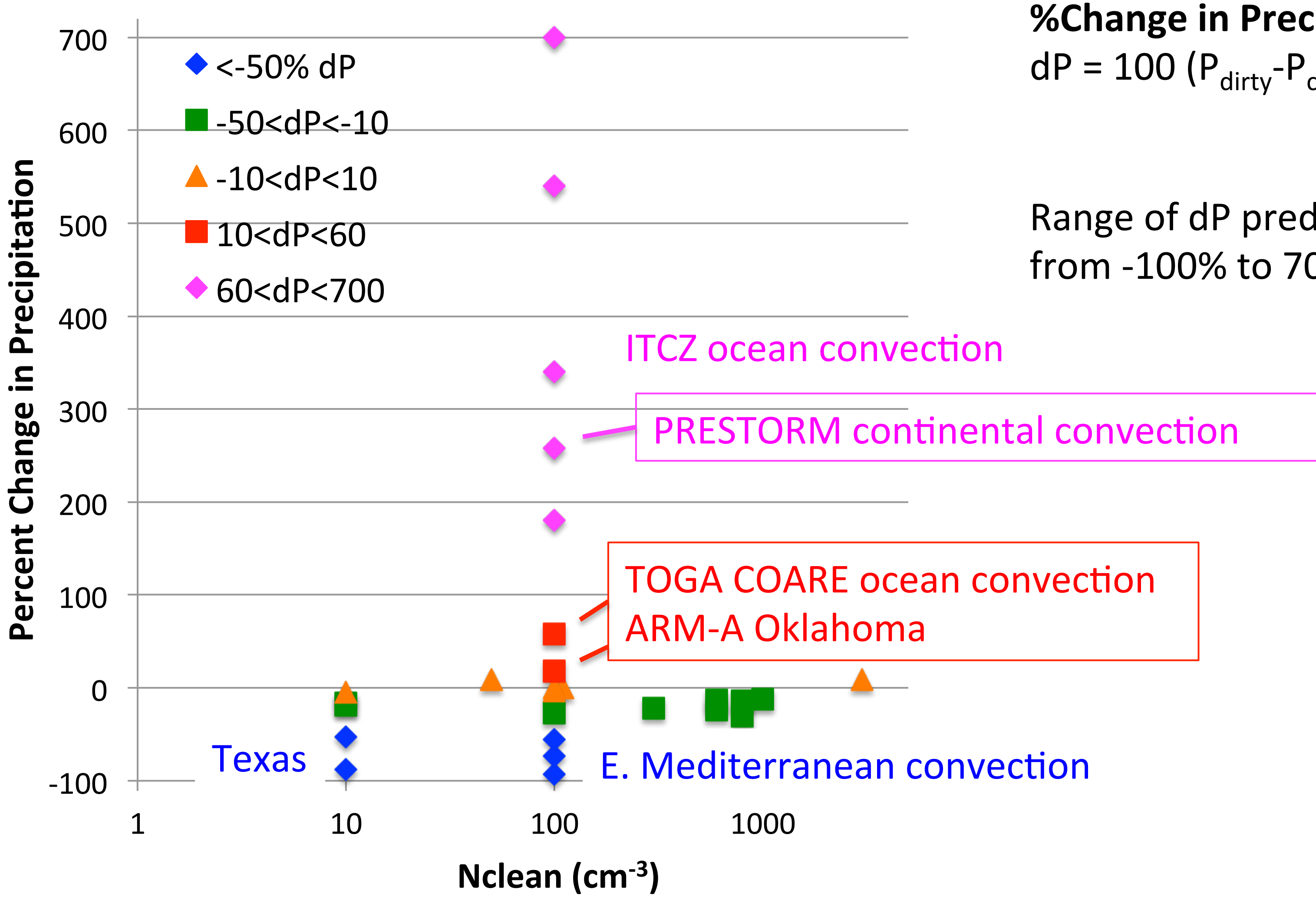
- Relative Humidity
- Cloud Type
- Wind Shear

Khain et al. (2008) *J. Atmos. Sci.*
→ More precipitation in more humid regions

Van den Heever et al. (2011) simulation of tropical convection found that for high CCN
→ Less precipitation from shallow clouds
→ More precipitation in deep convective clouds
→ Mixed response in moderate convective storms

Tao et al. (2012) *Rev. Geophys.*

27 Simulation Sensitivity Cases Reported in Tao et al. (2012)



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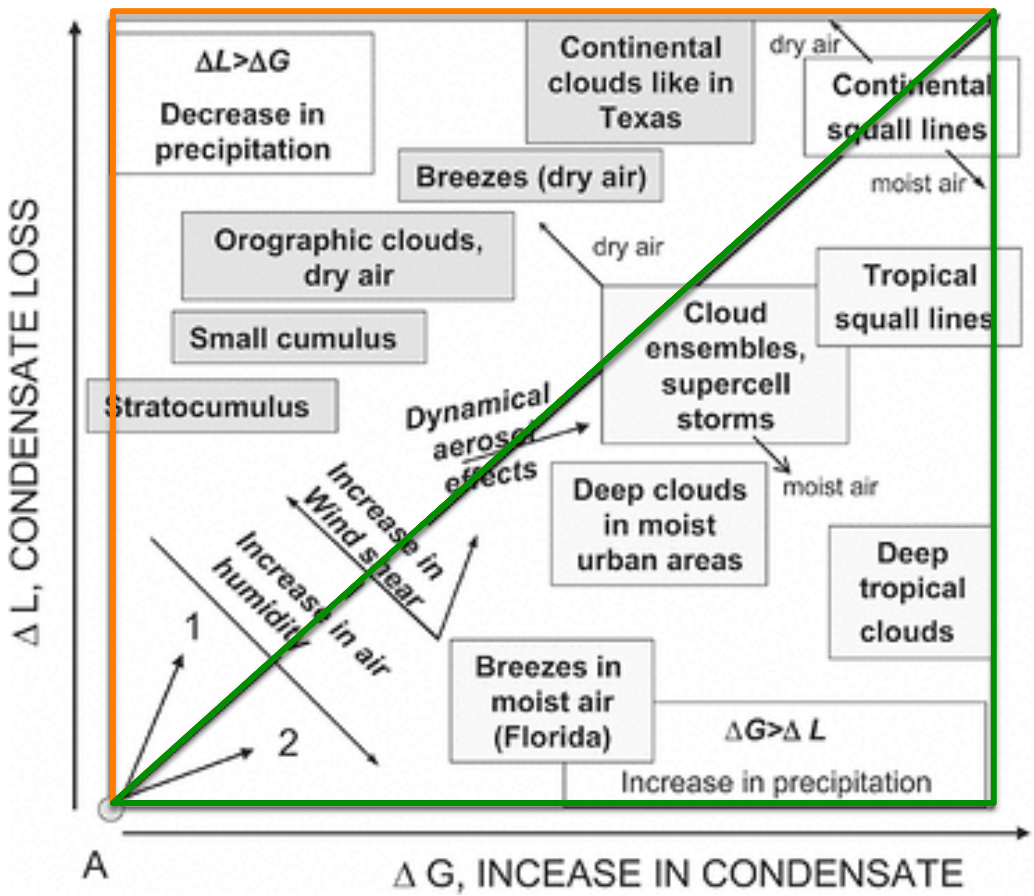
Tao et al. (2012) *Rev. Geophys.*

Relative Humidity Affects Aerosol Effects on Precipitation



Khain et al. (2008) state relative humidity affects condensation rate.

G = condensate mass formed by drop condensation and ice deposition

L = rain, snow, graupel loss due to evaporation and sublimation

Precipitation = G – L

ΔP = ΔG - ΔL

Decrease in precipitation with aerosol concentraiton

Increase in precipitation with aerosol concentration

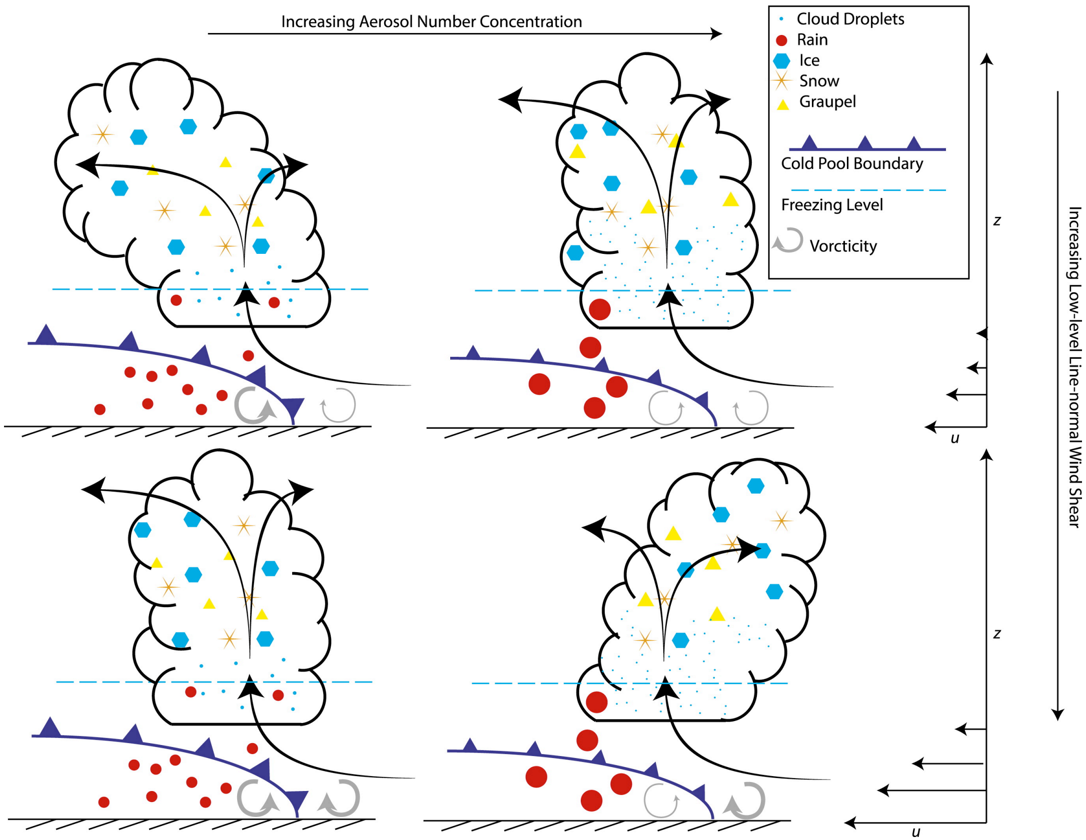
Van den Heever et al. (2011) simulation of tropical convection found that for high CCN

→ Less precipitation from shallow clouds
→ More precipitation in deep convective clouds
→ Mixed response in moderate convective storms

Khain et al. (2008) *J. Atmos. Sci.*

Aerosols and Storm Dynamics of a Squall Line

Lebo and Morrison (2014)



Based on Rotunno et al (1988) theory

Aerosols affect the raindrop size distribution, altering the bulk rain evaporation rate and cold pool intensity

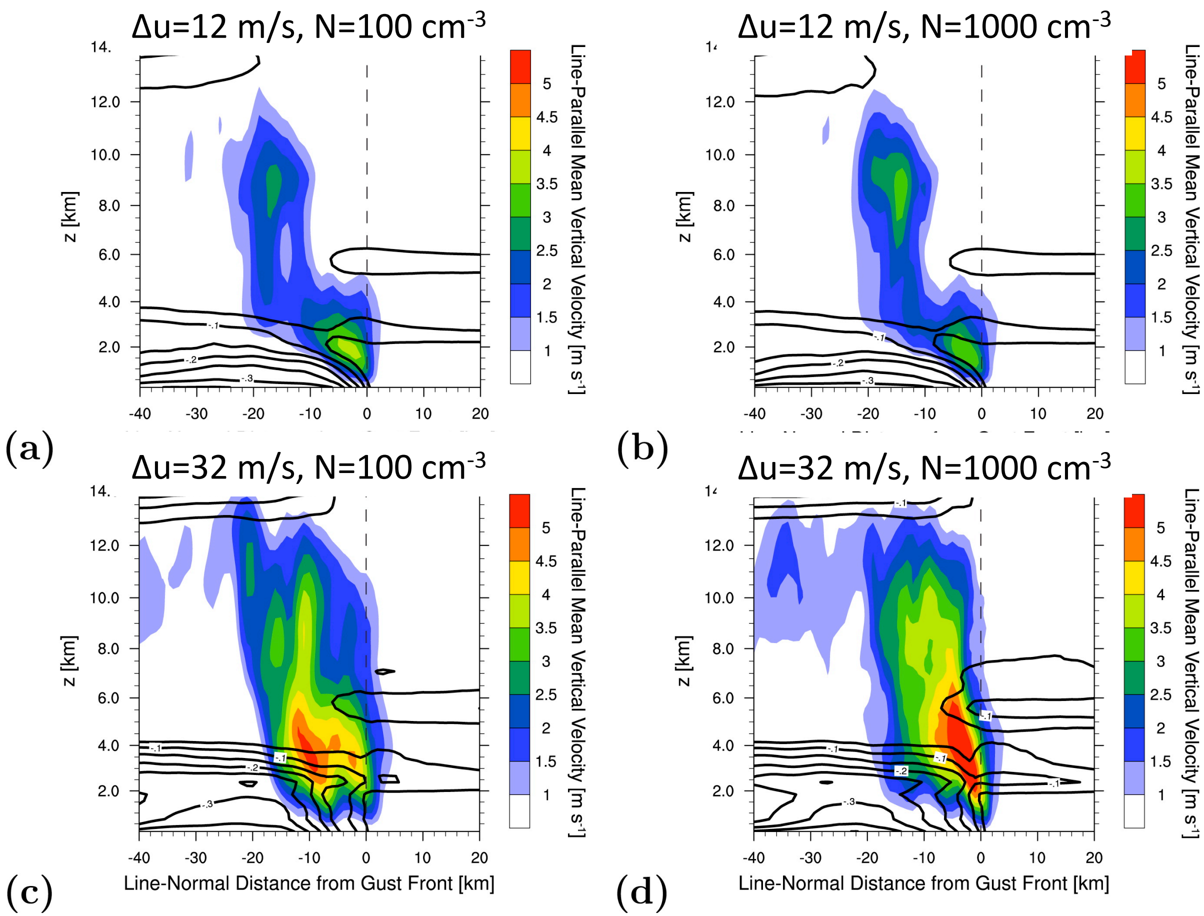
The balance between the cold pool induced circulations with the low-level environmental shear is modified

Causes an intensification of squall line in weak wind shear, and weakening of squall line in strong wind shear environments

Lebo and Morrison (2014) *Mon. Weather Rev.*

Aerosols and Storm Dynamics of a Squall Line

Line Parallel Mean Vertical Velocity



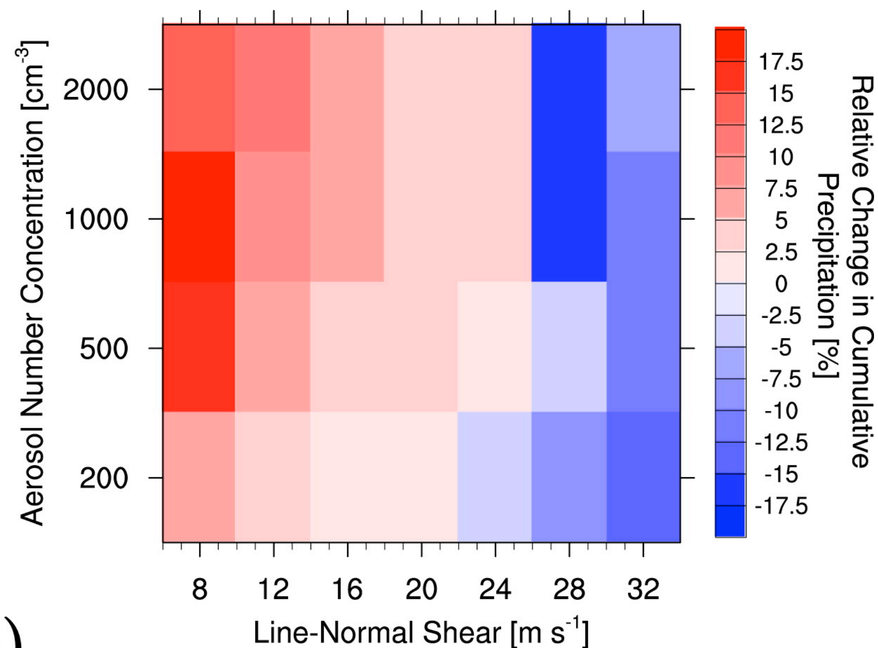
Based on Rotunno et al (1988) theory

Updrafts are stronger and more vertical for high aerosol loading and high shear

Lebo and Morrison (2014) *Mon. Weather Rev.*

Aerosols and Storm Dynamics of a Squall Line

Change in Precipitation (%)



b)

ΔP as function of aerosol number concentration and line-normal shear relative to Nclean = 100 cm^{-3}

Increased ΔP , Decreased ΔP

Lebo and Morrison (2014) *Mon. Weather Rev.*

Previous Studies

Nearly all previous CRM studies used idealized aerosol concentrations (N_{CCN}, N_{GCCN}, N_{IN})

Very few CRM studies compared model results with observed cloud structures, organization, radar reflectivities, aerosol concentrations, etc.

→ Real meteorology cases can be generated with mesoscale models such as WRF (weather research and forecasting model)
→ Realistic distributions of aerosols can be produced with models coupled with aerosols and chemistry, e.g. WRF-Chem
→ More challenging to represent convection well and to predict aerosol concentrations (mostly because of emissions)

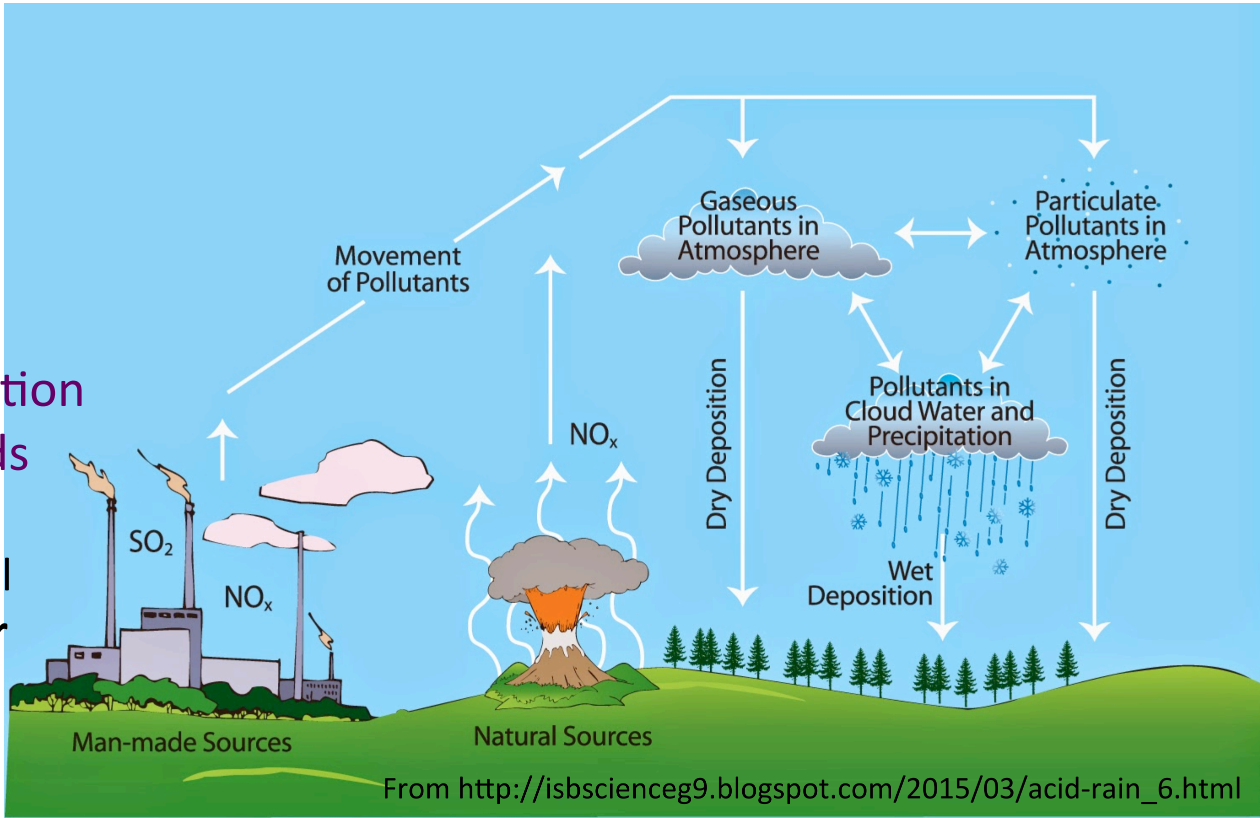
Weather Research and Forecasting Model Coupled with Chemistry (WRF-Chem)

Numerical weather and chemical constituent prediction
Wide range of applications 10s meters to 1000s kilometers
→ Cloud resolving scales with domains of up to 1000 km and grid spacings < 4 km

Chemistry is calculated at each meteorological time step
Emissions,
Transport,
Chemical transformations,
Removal by precipitation,
Removal by dry deposition

Effects of aerosols on radiation
Effects of aerosols on clouds

Chemical properties of aerosol represented with **κ parameter**



From http://isbscienceg9.blogspot.com/2015/03/acid-rain_6.html

Using WRF-Chem to Study Aerosol-Cloud Interactions

Chapman et al. (2009) implemented Abdul-Razzak and Ghan (2002) cloud droplet activation scheme to bulk cloud physics scheme in WRF → predict drop number

Technique extended to Morrison et al. (2009) double-moment cloud physics scheme

Some aerosol-cloud-precipitation CRM convection studies using WRF-Chem:

Ntelekos et al. (2009) NE United States
Fan et al. (2012, 2013, 2015)
Eidhammer et al. (2014) North America monsoon
Saide et al. (2015) SE United States tornadic event
Sarangi et al. (2015) Gangetic Basin, India
Fan et al. (2015) SW China
Yang et al. (2016) Central China

Recent WRF-Chem versions also include aerosols affecting parameterized convection

Using WRF-Chem to Study Aerosol-Cloud Interactions

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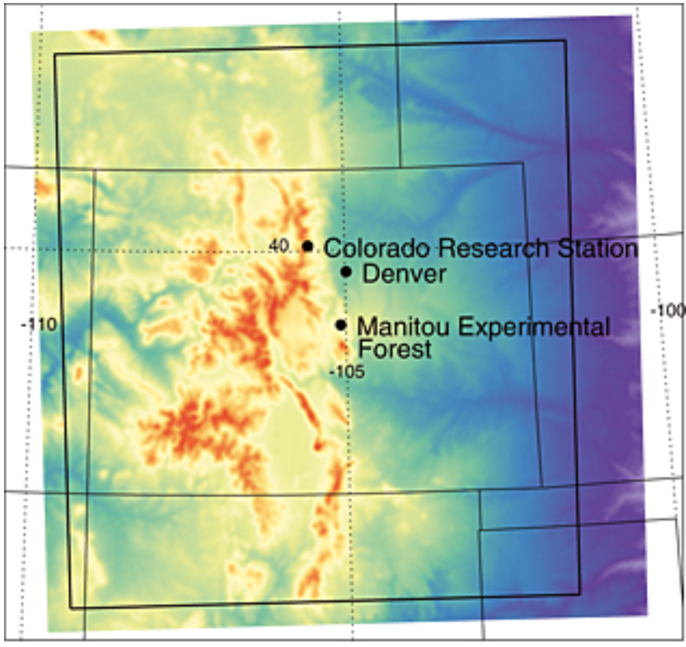
Sarangi et al. (2015) Gangetic Basin, India
Fan et al. (2015) SW China
Yang et al. (2016) Central China

Aerosol microphysical impact on summer convection in Rocky Mountain Region (Eidhammer et al., 2014)

WRF-Chem simulations over 820 x 820 km^2 domain using 3 km grid spacing for 3-day simulations
Sub region analyzed to remove potential effects of boundaries
First 12 hours are spin up and not analyzed

Gas-phase chemistry (CBMZ) but no secondary organic aerosol production
Sectional-approach for representing aerosols (MOSAIC 8-bin)
Cloud physics is Purdue Lin scheme with drop activation linked to aerosols

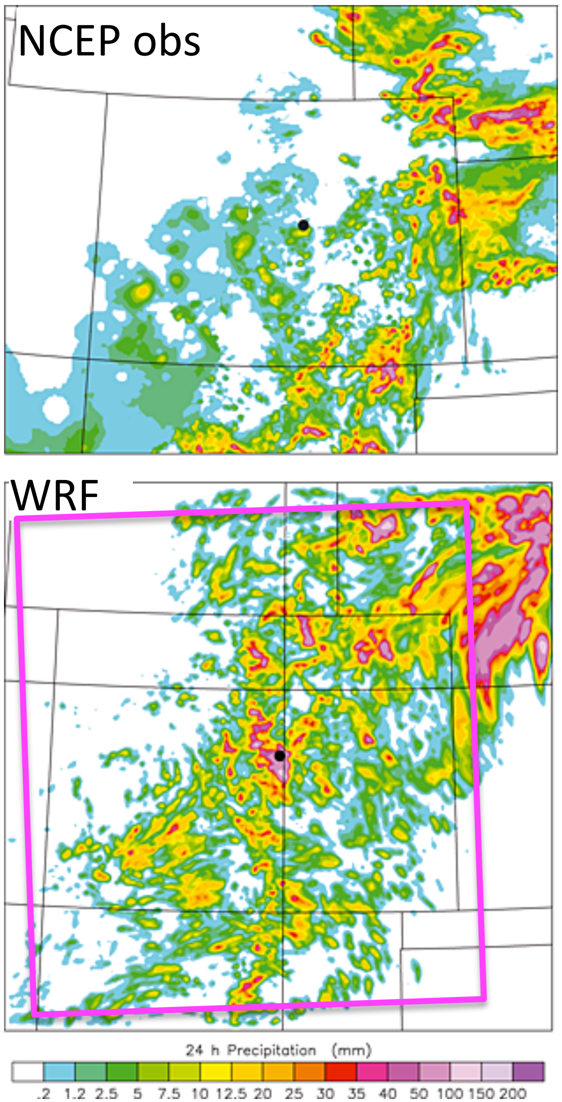
Anthropogenic emissions from EPA NEI 2005
Biogenic emissions calculated online (MEGAN)
No wildfire emissions



Model domain and sub-region for analysis

Eidhammer et al. (2014) *J. Geophys. Res.*

WRF-Chem Prediction of Precipitation



24-hr cumulative precipitation ending at 12 UTC 5 August

More precipitation predicted than observed (top)

Analysis region removes much of this overprediction

→ Challenging to represent storms as well with "real meteorology" cases

Eidhammer et al. (2014) *J. Geophys. Res.*

Aerosol effects on summertime convection

→ Do aerosols affect precipitation on regional scale?

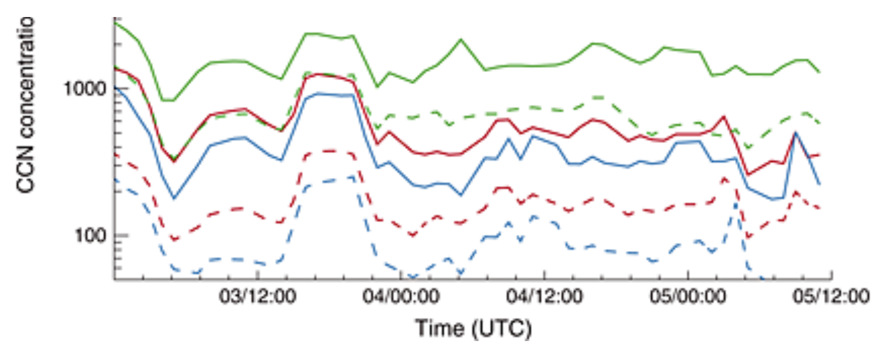
In this study, aerosols affect only clouds and not radiation

Aerosol concentrations are controlled by the initial and boundary conditions (low anthropogenic emissions in region)
Initial and boundary conditions from global model (MOZART)

Simulations:

	CCN
1. Control	700 cm^{-3}
2. Aerosol mass conc. are 10xControl	1500 cm^{-3}
3. Aerosol mass conc. are 0.2xControl	400 cm^{-3}
4. Aerosol mass conc. are 0.1xControl	< 400 cm^{-3}

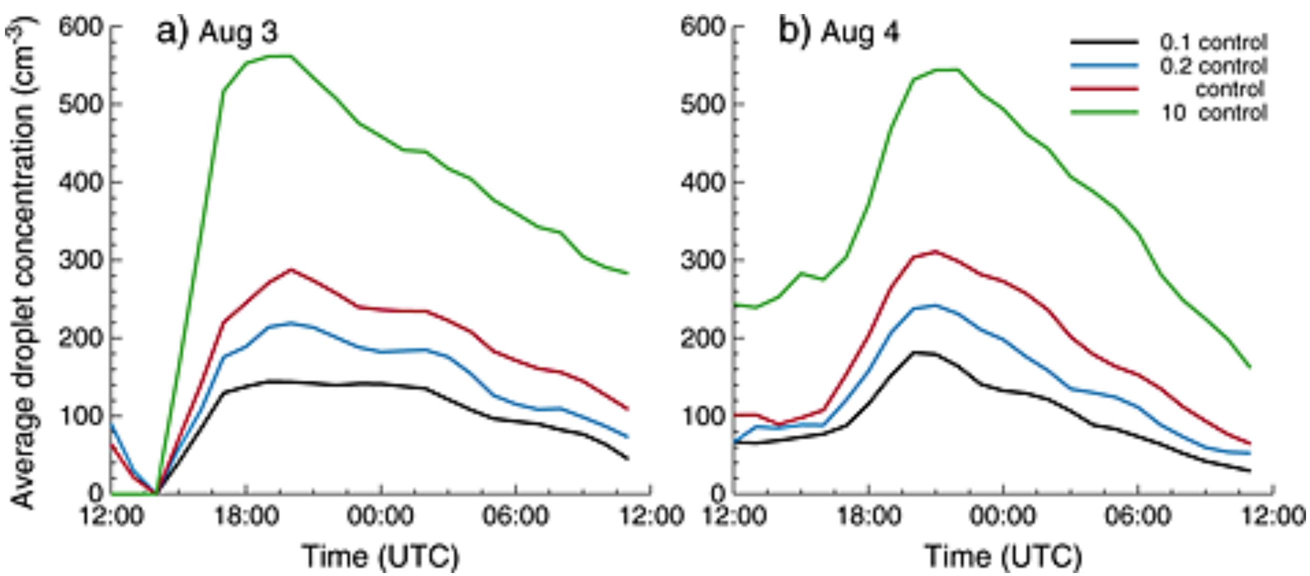
CCN conc as function of time



Eidhammer et al. (2014) *J. Geophys. Res.*

Aerosol affects cloud drop concentration

Increased aerosol mass concentration increases cloud droplet number concentrations, and vice versa



CCN

< 400 cm^{-3}

400 cm^{-3}

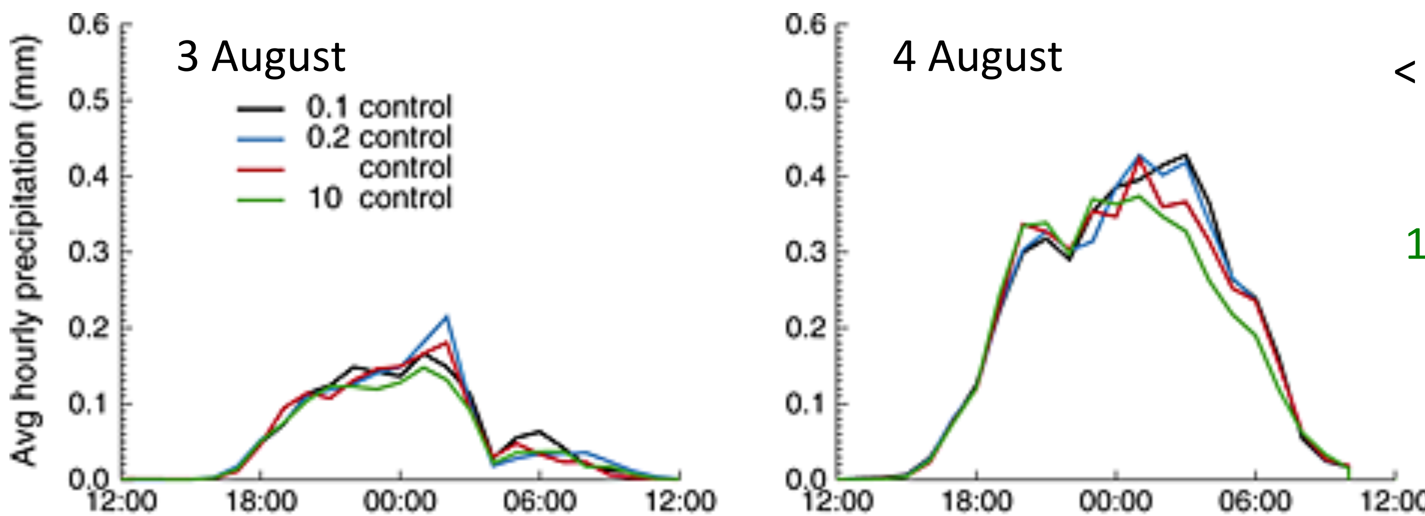
700 cm^{-3}

1500 cm^{-3}

Eidhammer et al. (2014) *J. Geophys. Res.*

Aerosol effects on precipitation

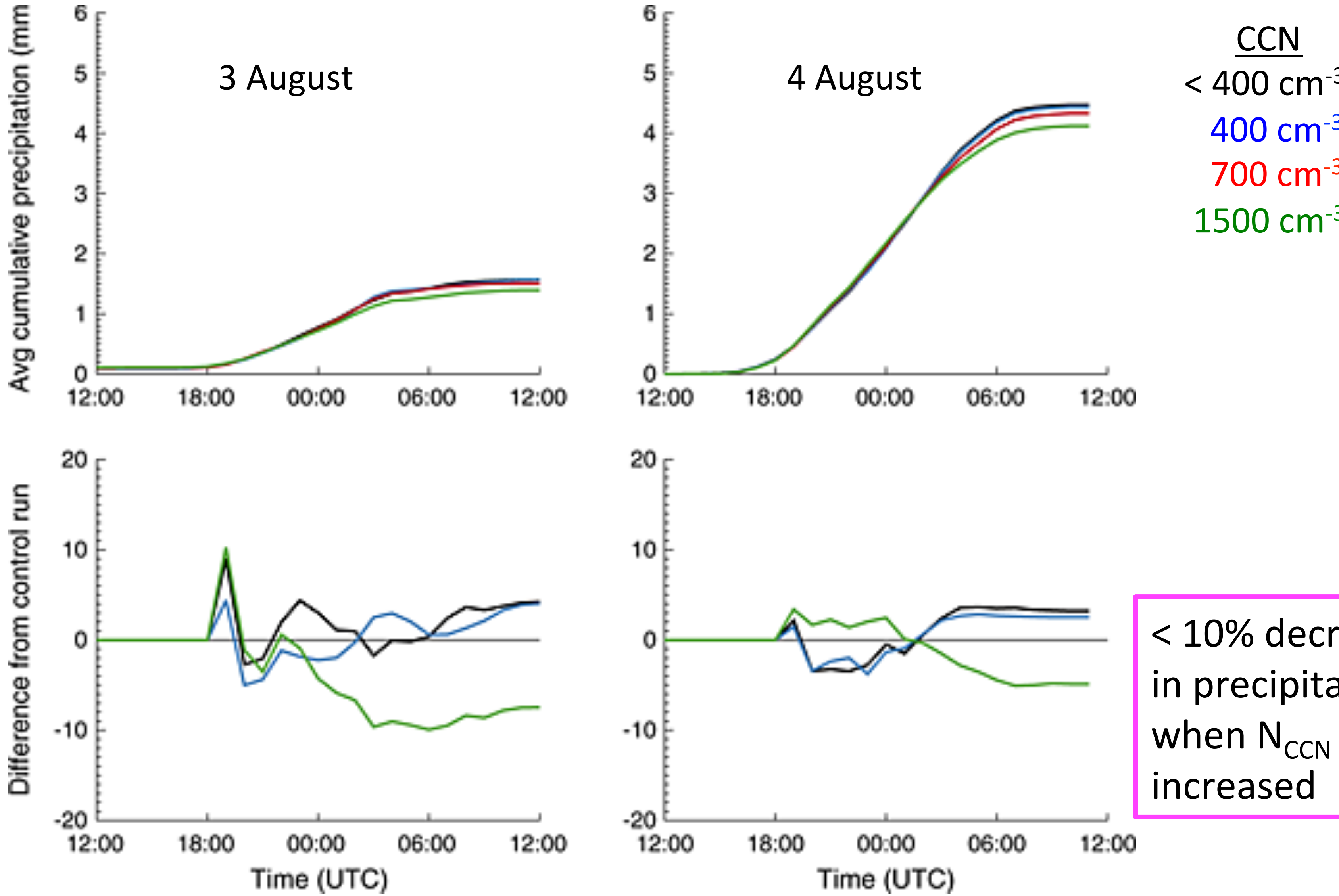
Hourly rain rate from four simulations
(simulations integration: 2-5 August)



CCN
< 400 cm^{-3}
400 cm^{-3}
700 cm^{-3}
1500 cm^{-3}

Eidhammer et al. (2014) *J. Geophys. Res.*

Precipitation changes are <10%



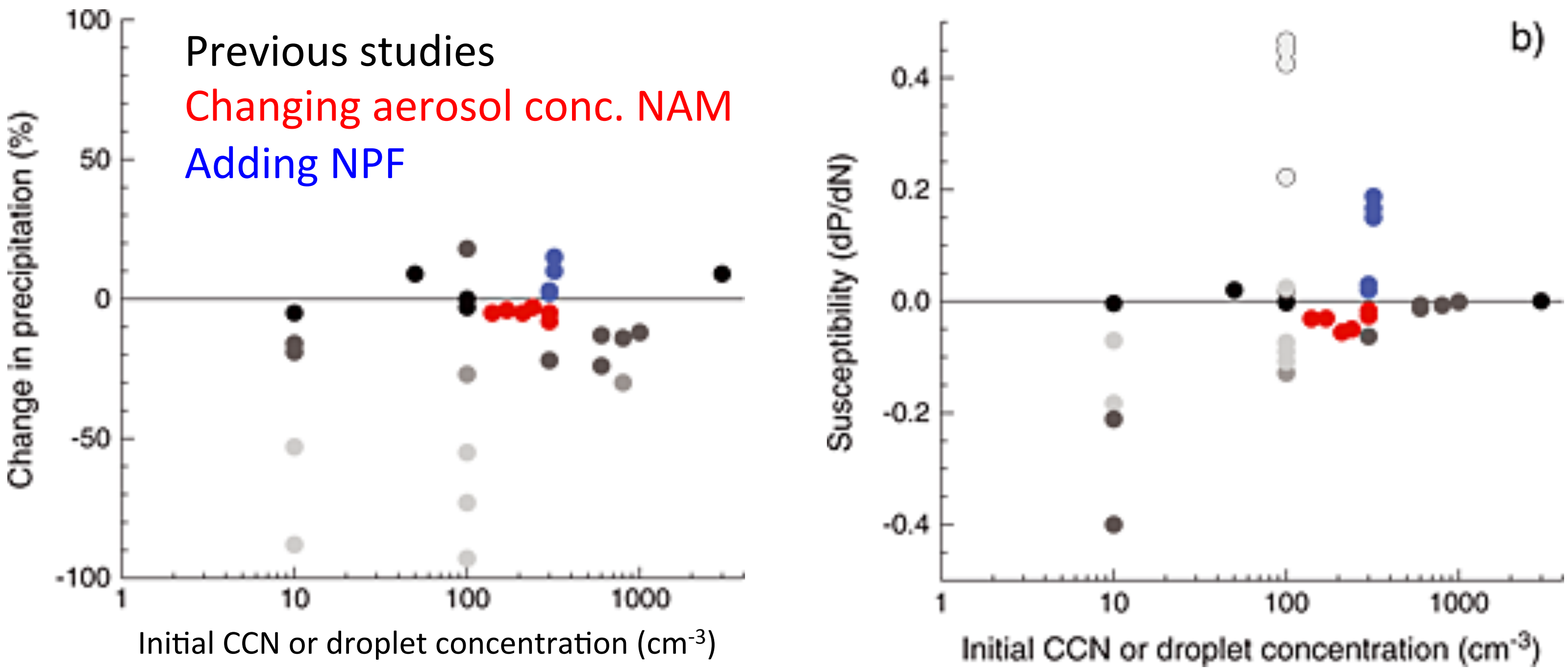
< 10% decrease in precipitation when N_{CCN} increased

Eidhammer et al. (2014) *J. Geophys. Res.*

Comparison of dP and dP/dN to Previous Studies

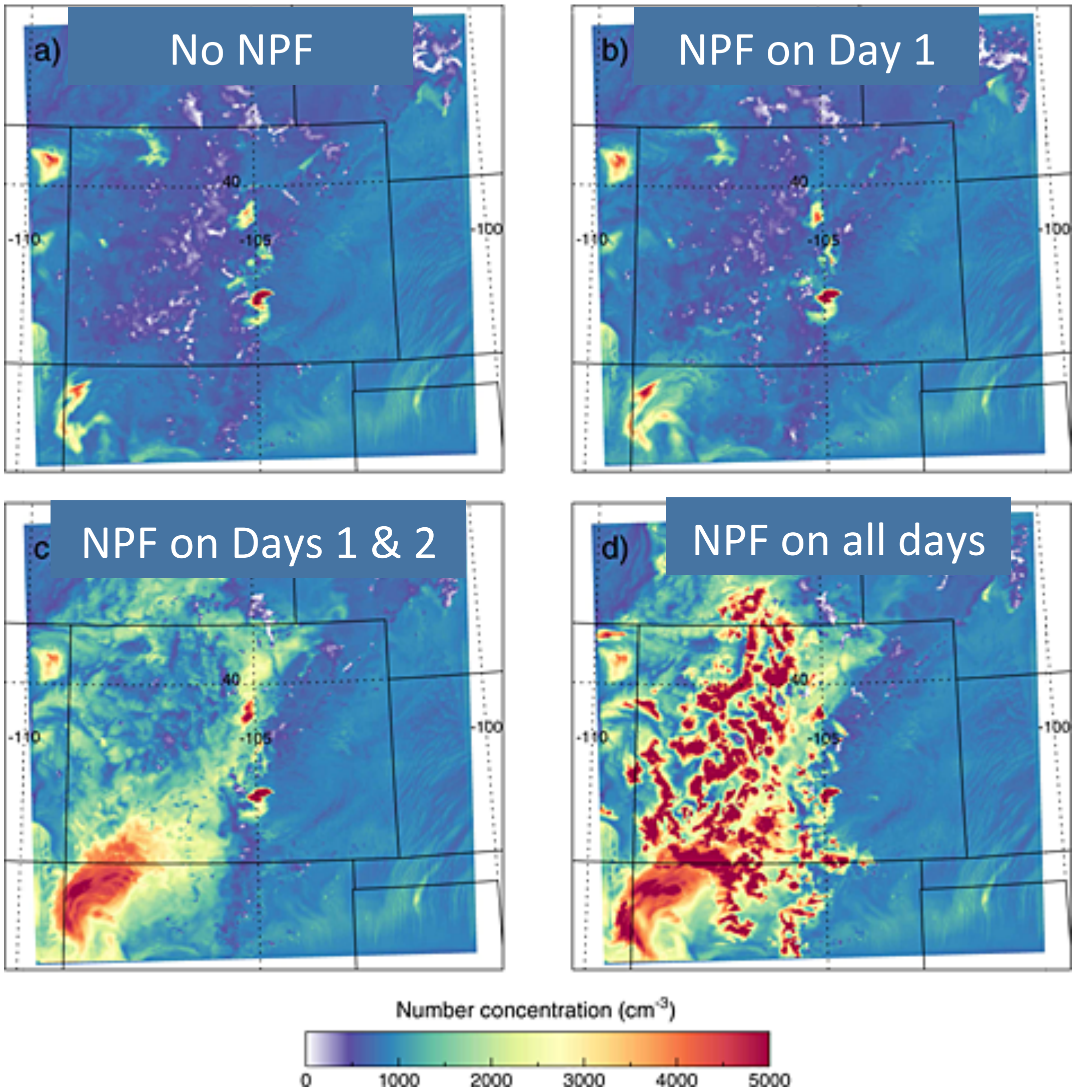
Increasing aerosols cause small decrease in precipitation over a large region -- suggests storms occur in slightly different locations, not changing overall condition; longer simulation also captures regional effect

Similar results to two studies of Florida storm, a New Mexico storm, GATE case (ocean), frontal system in Taiwan



Eidhammer et al. (2014) *J. Geophys. Res.*

New Particle Formation from Biogenic Organic Compounds



Representation of NPF:

Emission rate of 0.5 μg m^{-2} s^{-1}

Evergreen and needleleaf forests

12-18 local time (afternoon)

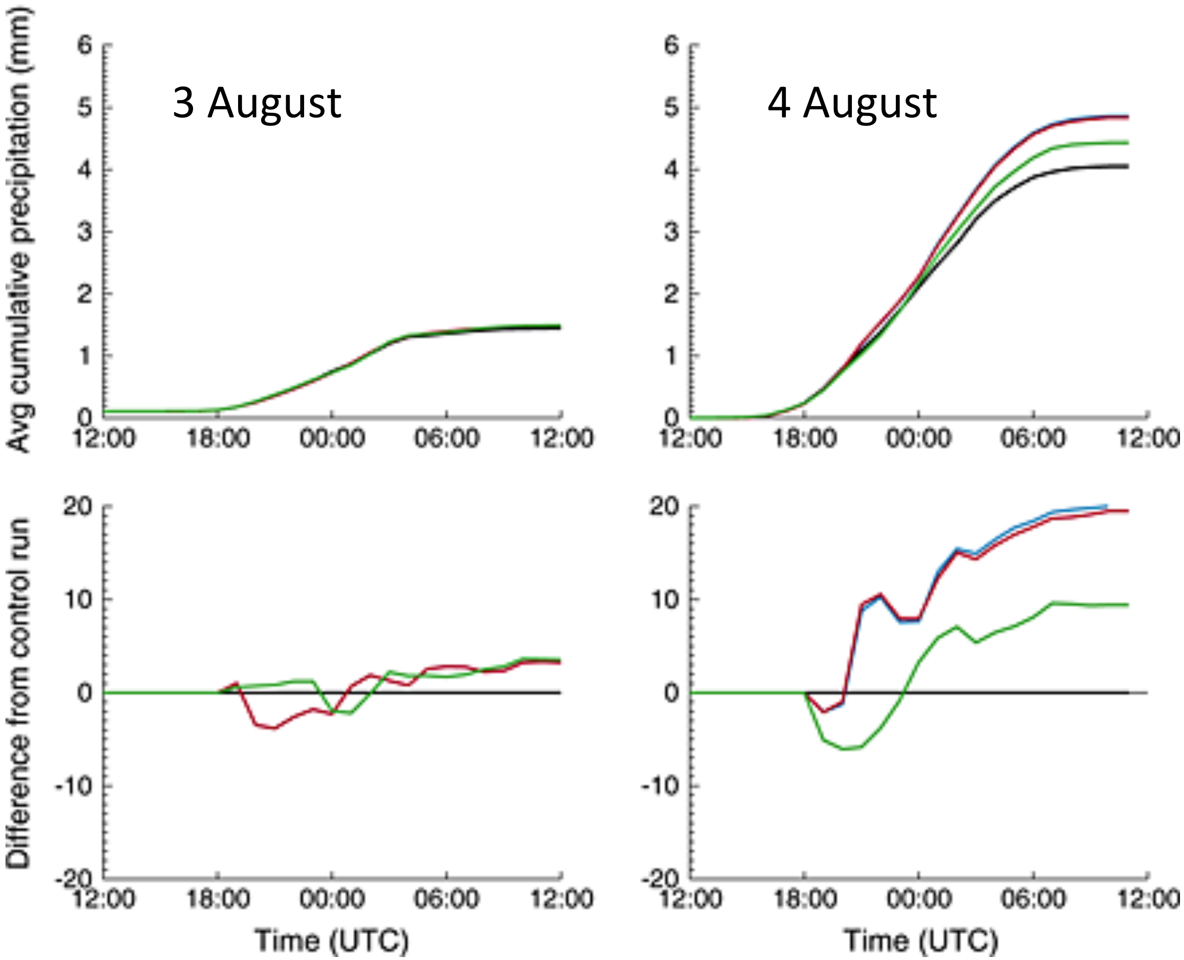
Aerosol concentrations in smallest size bin at ~1700 m above ground

→ Affects hygroscopicity of CCN (organic aerosols)

→ Increases cloud drop concentration

Eidhammer et al. (2014) *J. Geophys. Res.*

New Particle Formation Increases Precipitation

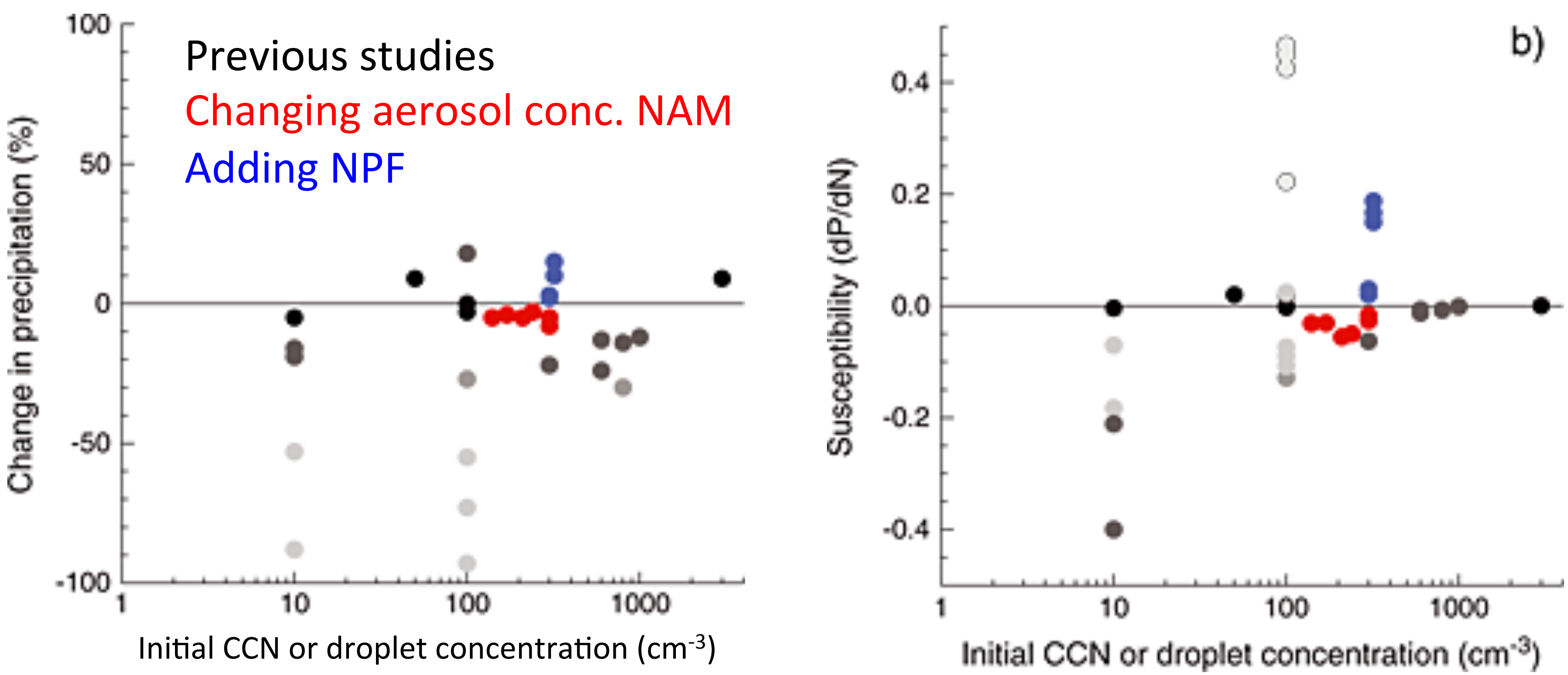


Cumulative Precipitation increases by 8-20%

Eidhammer et al. (2014) *J. Geophys. Res.*

Comparison of dP and dP/dN to Previous Studies

Increasing small aerosols cause increase in precipitation over a large region
-- dynamic system of meteorology, natural and anthropogenic emissions



Eidhammer et al. (2014) *J. Geophys. Res.*

Regional-Scale, Multi-day Simulations of Real Meteorology

Evaluation of results with observations is possible!
Challenge of doing "real meteorology" cases in representing storms and precipitation well

Small effect on precipitation when aerosol concentrations change
New particle formation may contribute to increased precipitation

These small changes in regional-scale precipitation may be of same order as changes in model parameterizations, e.g. PBL schemes, cloud physics schemes

Eidhammer et al. (2014) *J. Geophys. Res.*

Using WRF-Chem to Study Aerosol-Cloud Interactions

Chapman et al. (2009) implemented Abdul-Razzak and Ghan (2002) cloud droplet activation scheme to bulk cloud physics scheme in WRF → predict drop number

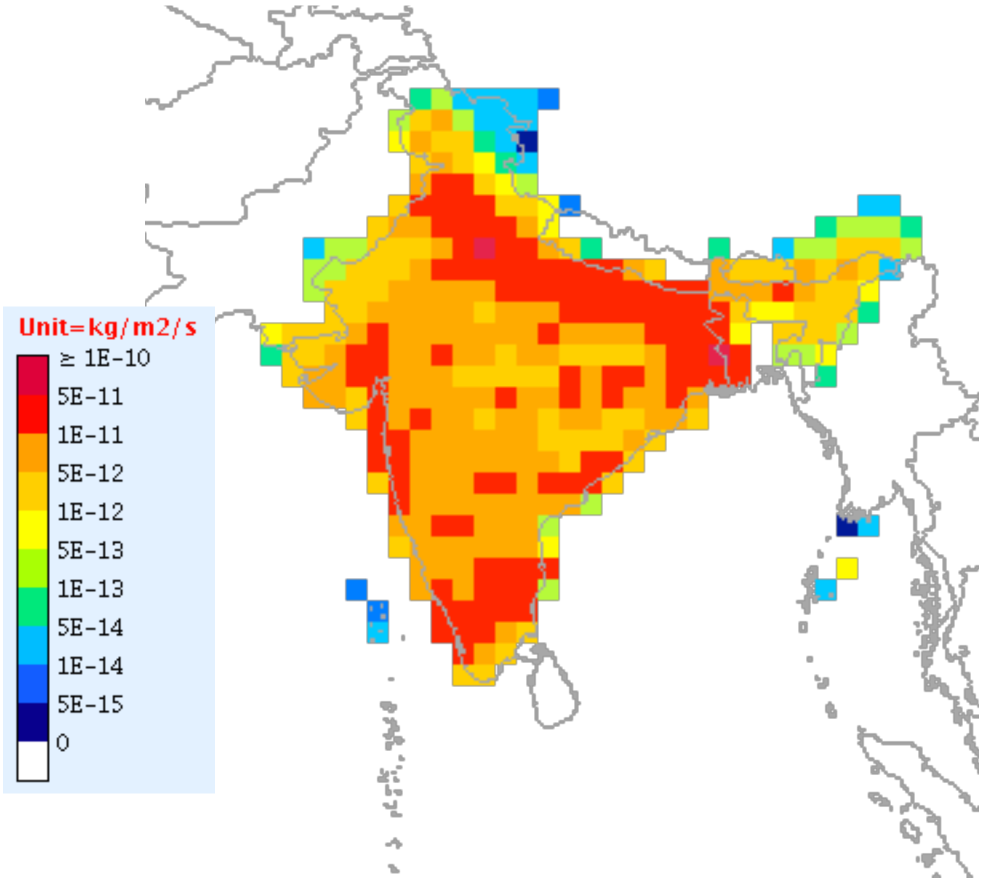
Technique extended to Morrison et al. (2009) double-moment cloud physics scheme

Some aerosol-cloud-precipitation CRM convection studies using WRF-Chem:

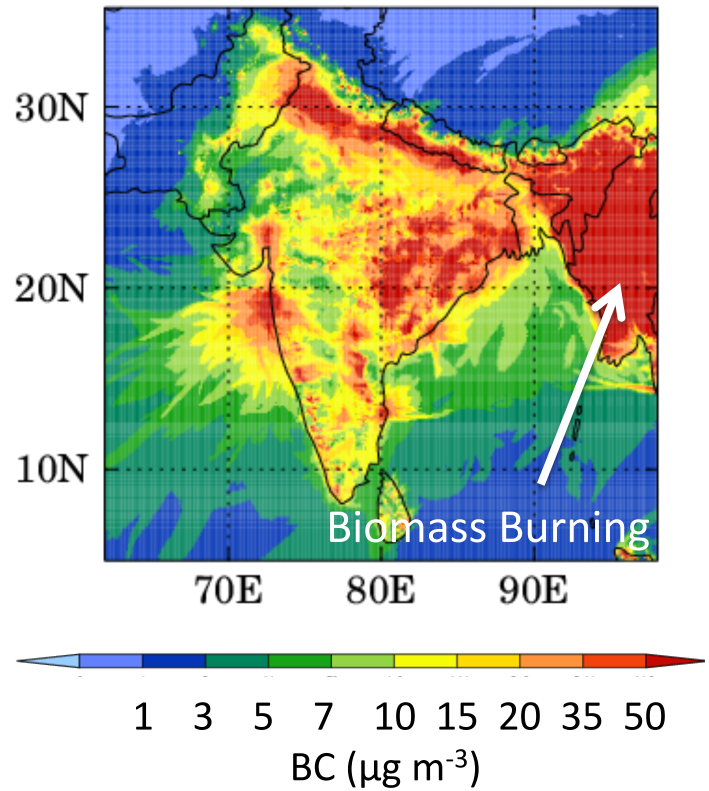
Ntelekos et al. (2009) NE United States
Fan et al. (2012, 2013, 2015)
Eidhammer et al. (2014) North America monsoon
Saide et al. (2015) SE United States tornadic event
Sarangi et al. (2015) Gangetic Basin, India
Fan et al. (2015) SW China
Yang et al. (2016) Central China

Regional-Scale, Multi-day Simulations for India

Anthropogenic Black Carbon Emissions for 2011 based on SAFAR inventory



Black Carbon Concentrations predicted by WRF-Chem



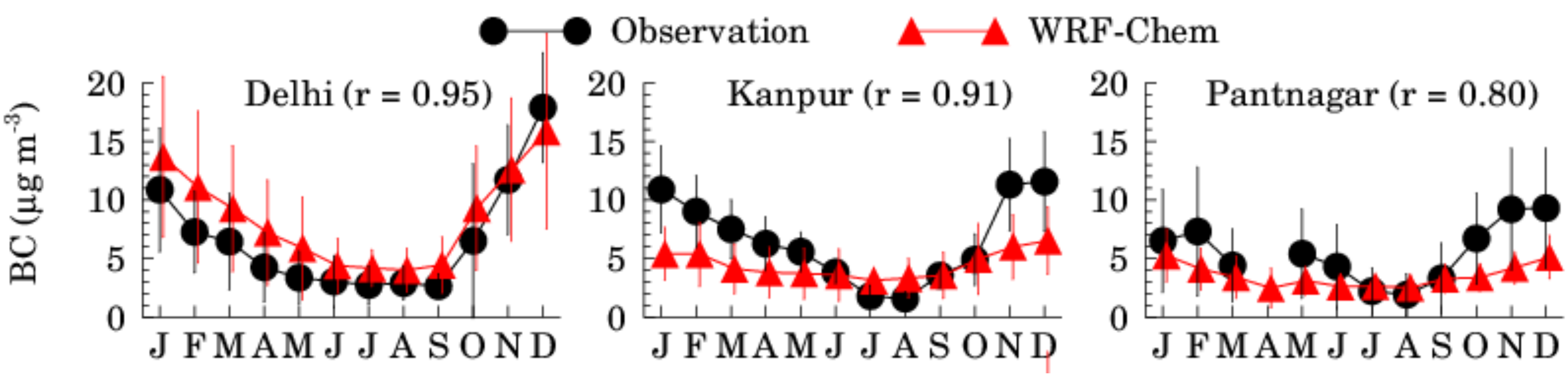
ECCAD: http://eccad.sedoo.fr/eccad_extract_interface/JSF/page_carte.jsf ; Kumar et al. (2015) *J. Geophys. Res.*

Regional-Scale, Multi-day Simulations for India

Black carbon and organic carbon contribute much more to aerosol composition

Impacts radiation (BC absorbs solar radiation)

Impacts hygroscopicity



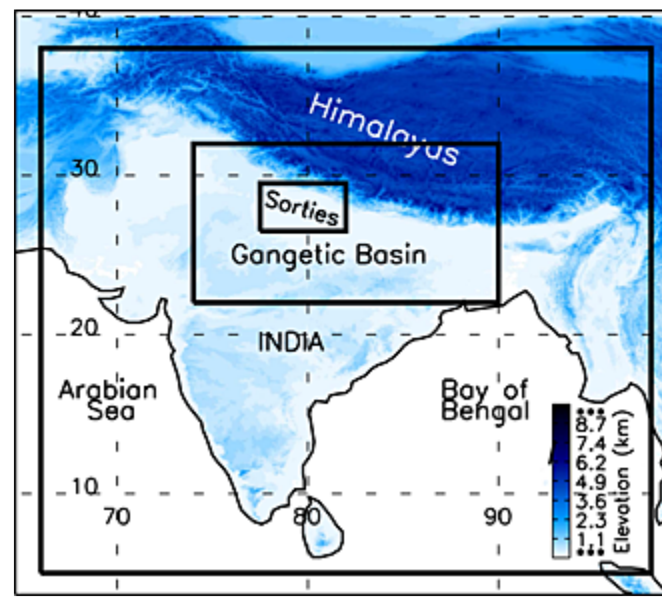
Kumar et al. (2015) *J. Geophys. Res.*

Aerosol-cloud associations over Gangetic Basin during a typical monsoon depression event using WRF-Chem simulation (Sarangi et al., 2015)

WRF-Chem simulations over 3 domains. Innermost using 3 km grid spacing
10-day simulations (3-day spin up time)
“CAIPEEX Sorties” region analyzed

Gas-phase chemistry (CBMZ) but no secondary organic aerosol production
Sectional-approach for representing aerosols (MOSAIC 4-bin)
Cloud physics is Morrison double-moment scheme with drop activation linked to aerosols

Anthropogenic emissions from MACCity (2010) and INTEX-B for PM2.5 and PM10 (2006)
Biogenic emissions calculated online (MEGAN)
Biomass Burning emissions (NCAR FINN model)



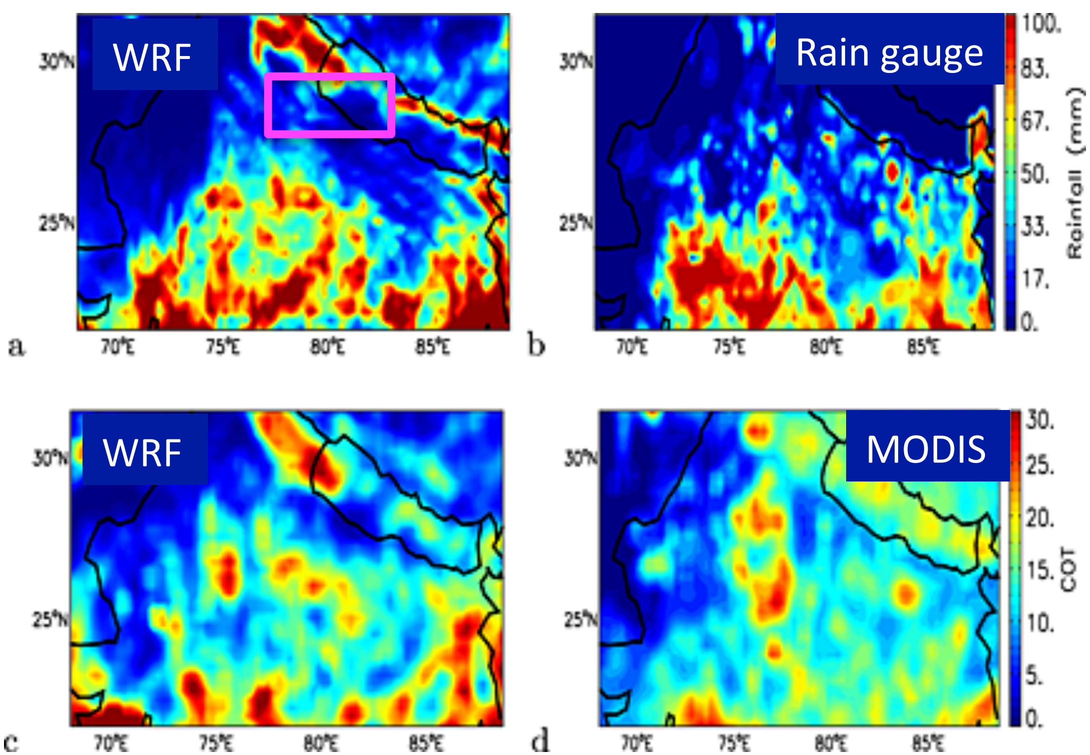
Sarangi et al. (2015) *J. Geophys. Res.*

WRF-Chem Prediction of Precipitation

More precipitation predicted than observed (top)

Analysis region removes much of this overprediction

→ Challenging to represent storms as well with "real meteorology" cases



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

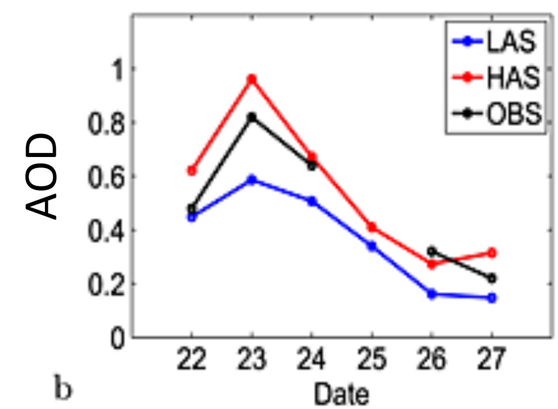
Northern India and Nepal
(top) accumulated rainfall
(bottom) cloud optical depth

Aerosol effects on monsoon convection

→ Do aerosols affect precipitation in Gangetic Plain?

In this study, aerosols affect both cloud physics and radiation

Aerosol anthropogenic emissions altered to evaluate changes

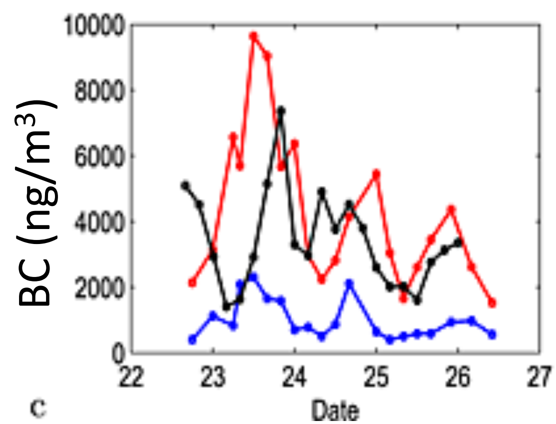


b

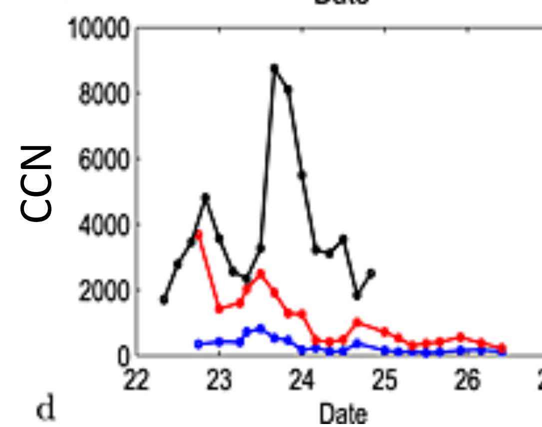
Simulations:

1. Low aerosol scenario
2. High aerosol scenario
   (emissions are 6x low aerosol scenario)

Compare with 2 sorties
from CAIPEEX campaign



c



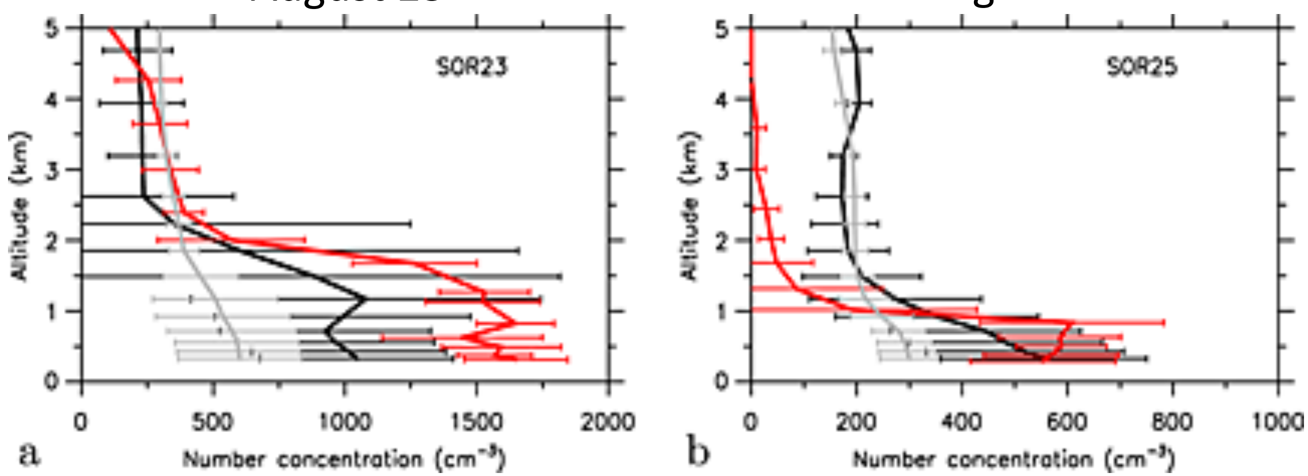
d

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

Aerosol prediction compared to aircraft data

Increased aerosol emissions give better agreement with observed aerosol number concentrations from flight

August 23 August 25



High aerosol scenario

Low aerosol scenario

Observations

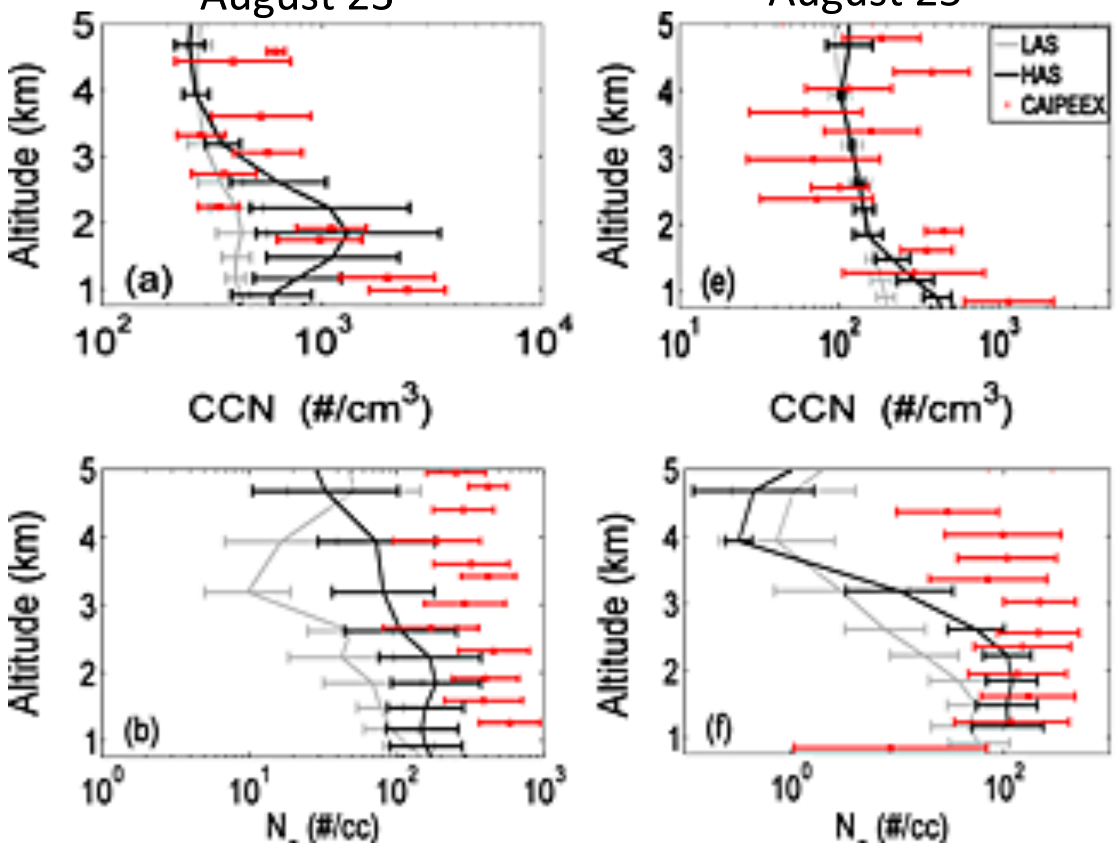
Sarangi et al. (2015) *J. Geophys. Res.*

Aerosol affects cloud drop concentration

Increased aerosol emissions give higher CCN and cloud drop number concentrations

August 23

August 25



High aerosol scenario

Low aerosol scenario

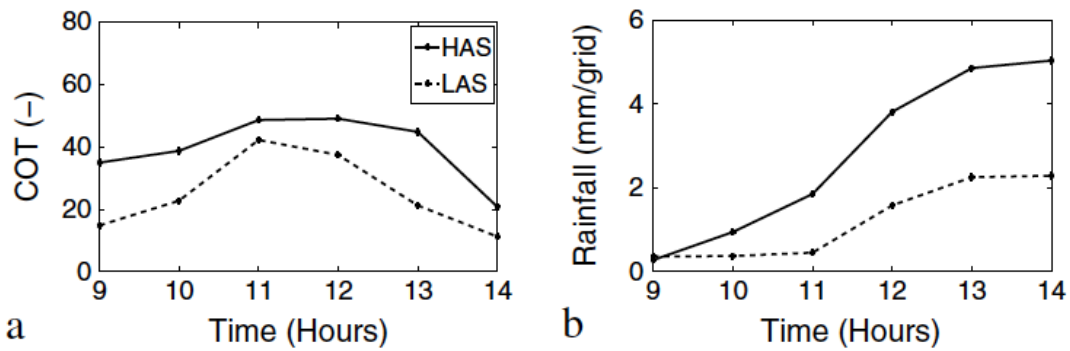
Observations

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

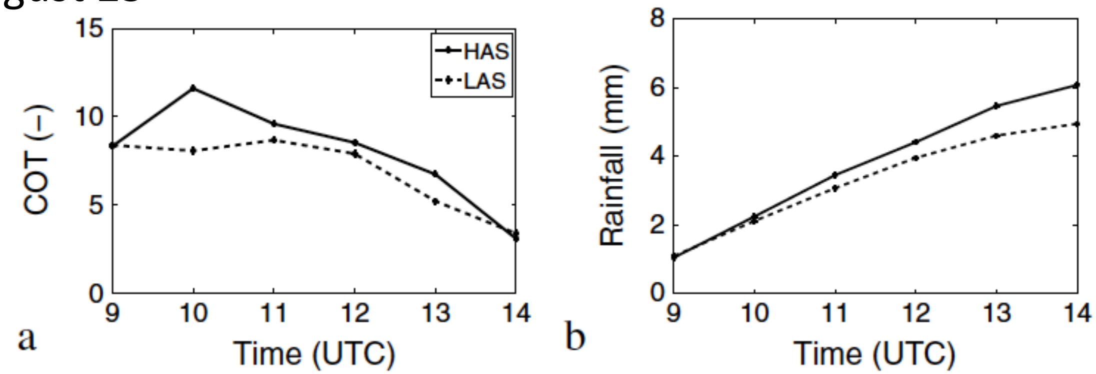
Aerosol affects cloud drop concentration

Increased aerosol emissions give higher CCN and cloud drop number concentrations

August 23



August 25



High aerosol scenario

Low aerosol scenario

More rain when aerosol emissions are 6x greater

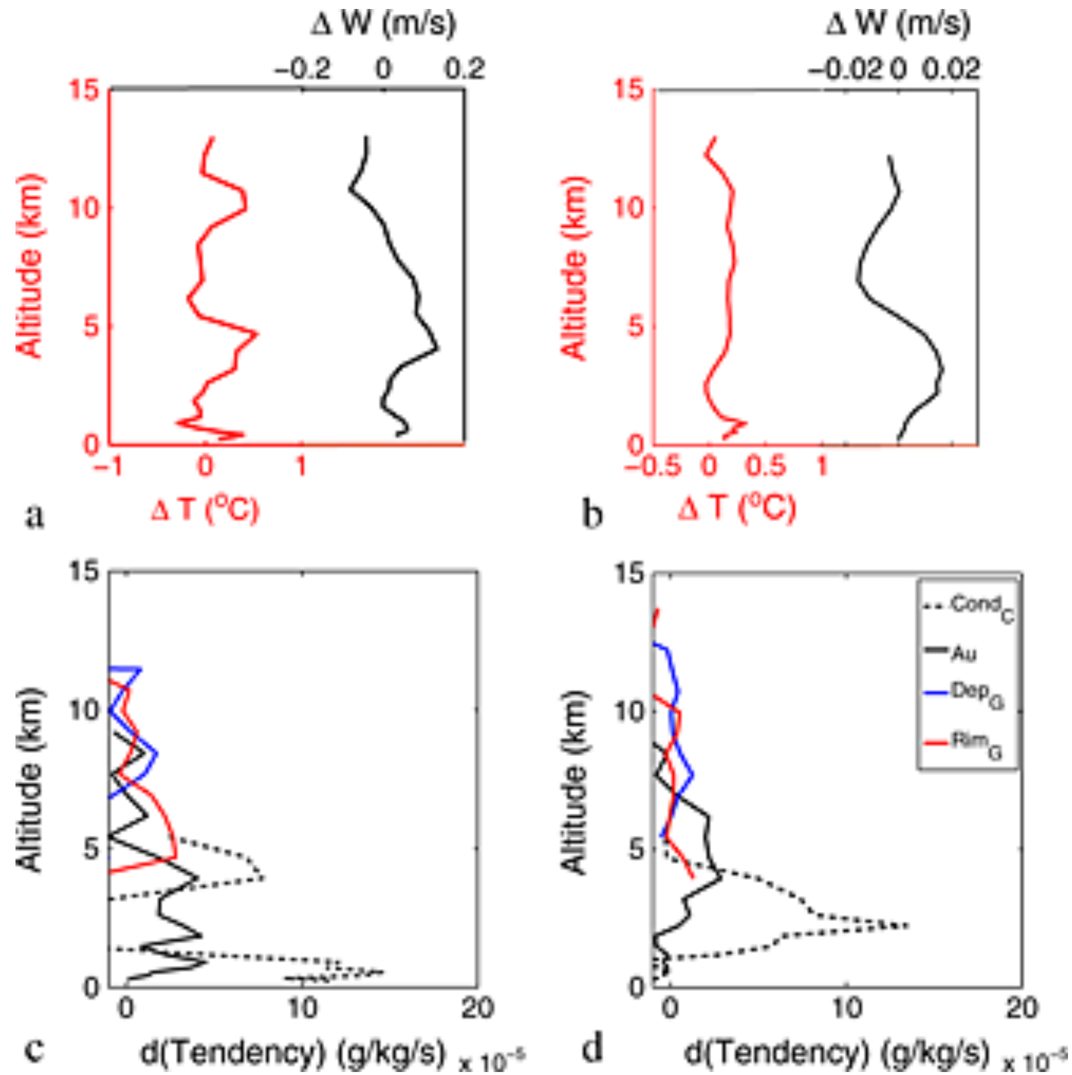
Higher cloud optical thickness for high aerosol case

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

Aerosol effects on storm structure and vertical velocity

High Aerosol – Low Aerosol
Temperature changes
CAPE increases by 300 J/kg
and 50 J/kg
Increase in updraft speed

High Aerosol – Low Aerosol
Condensation increases
Riming increases
Conversion from drops to
rain increases



August 23 August 25

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

Regional-Scale, Multi-day Simulations over Gangetic Plain

<u>Increasing Aerosol Concentrations in boundary layer via emissions:</u>

BC aerosol in PBL is absorbing radiation, heating PBL

→ increase in mean temperature and convective available potential energy (CAPE)

→ Formation of more, smaller cloud drops near cloud base

→ Both processes increased updraft velocities below the freezing level

→ Increased upward flux of cloud drops to mixed phase region, increases riming and cloud top height

→ Downdraft also intensifies (increased water loading)

→ Aerosol-induced cloud invigoration

Although aerosols were removed by precipitation during the first day (August 23), they were quickly replaced by the aerosol emissions

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

Mechanisms Proposed to Explain Precipitation Changes by Increasing Aerosol Concentrations

Increased Aerosol Concentrations Cause Decreased Precipitation:

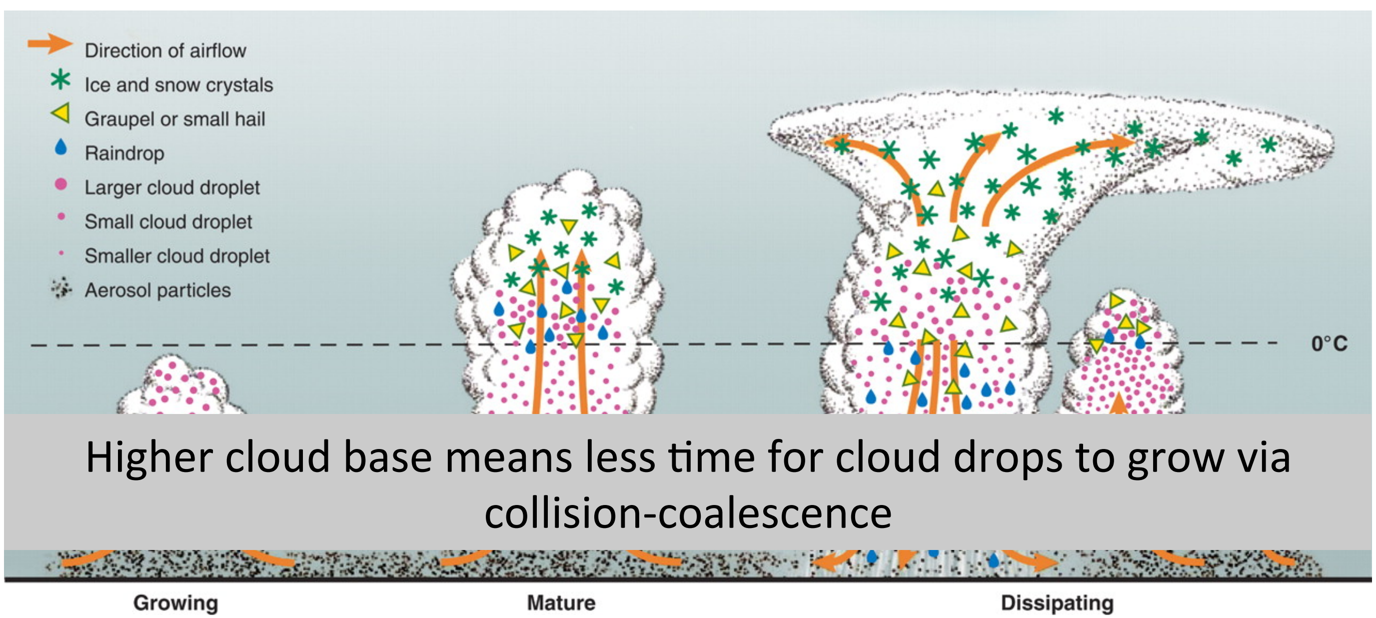
1. Less efficient collision-coalescence for producing rain due to more aerosols activating to produce more small cloud drops

Increased Aerosol Concentrations Cause Increased Precipitation:

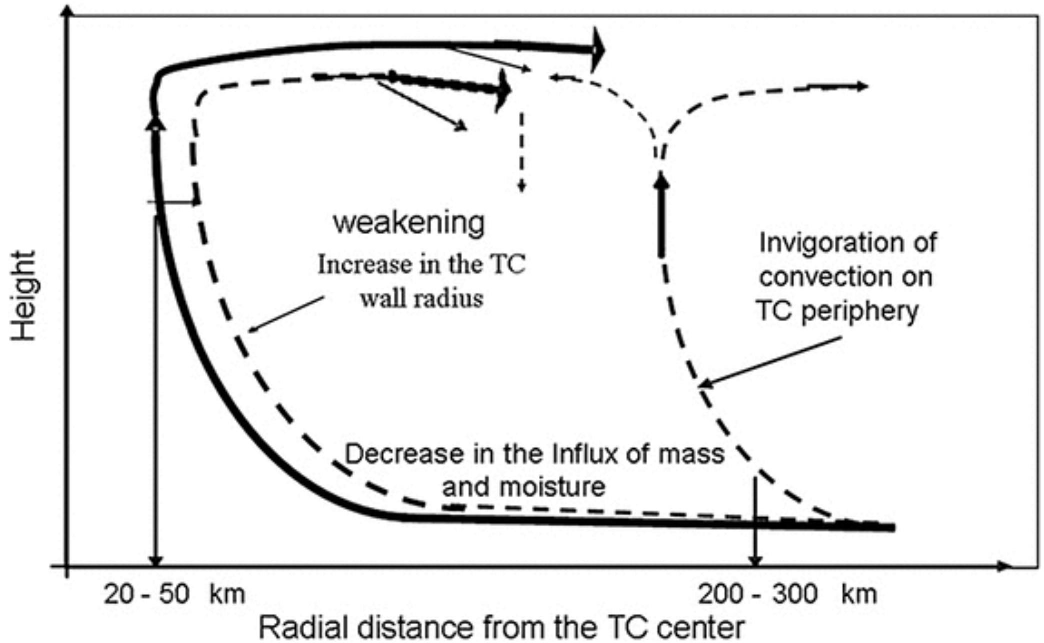
1. *Latent heat – Dynamic Effect*: small cloud drops lofted to above freezing level; Freezing of drops releases latent heat, enhancing updrafts
2. *Cool Pool Effect:* stronger evaporative cooling from more, but smaller, raindrops enhances strength of cold pool; interactions with wind shear can invigorate updrafts and convection
3. *Cold Microphysics Effect:* higher CCN concentrations increases total water content condensed enhancing ice physics processes – can lead to more or less precipitation

Other Factors to Consider in Explaining Precipitation Changes by Increasing Aerosol Concentrations

1. Relative Humidity – dry environment or moist environment
2. Wind shear
3. Cloud type – small clouds versus deep clouds and systems of storms
4. Type of aerosol – absorbing aerosols affect the thermodynamics of environment
5. Depth from cloud base to freezing level (warm cloud depth)



Schematic Depicting How Aerosols Affect Tropical Cyclones



- Invigorates outer rainbands
- Decreases the influx of mass and moisture to the center of the TC
- Weakens tropical cyclone convection in the wall of the eye
- Increases the radius of the eye

Khain et al. [2010].