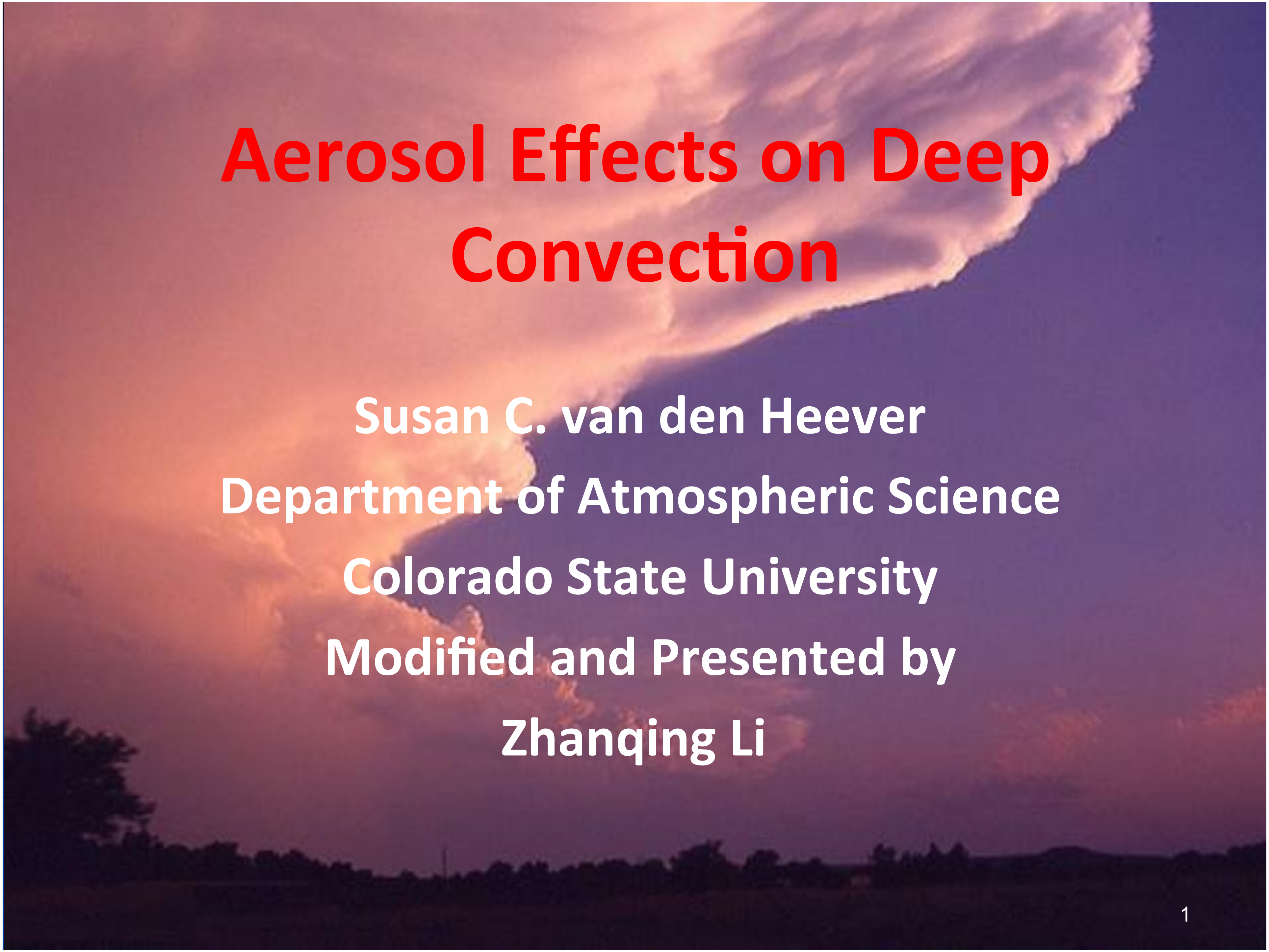

Aerosol Effects on Deep Convection

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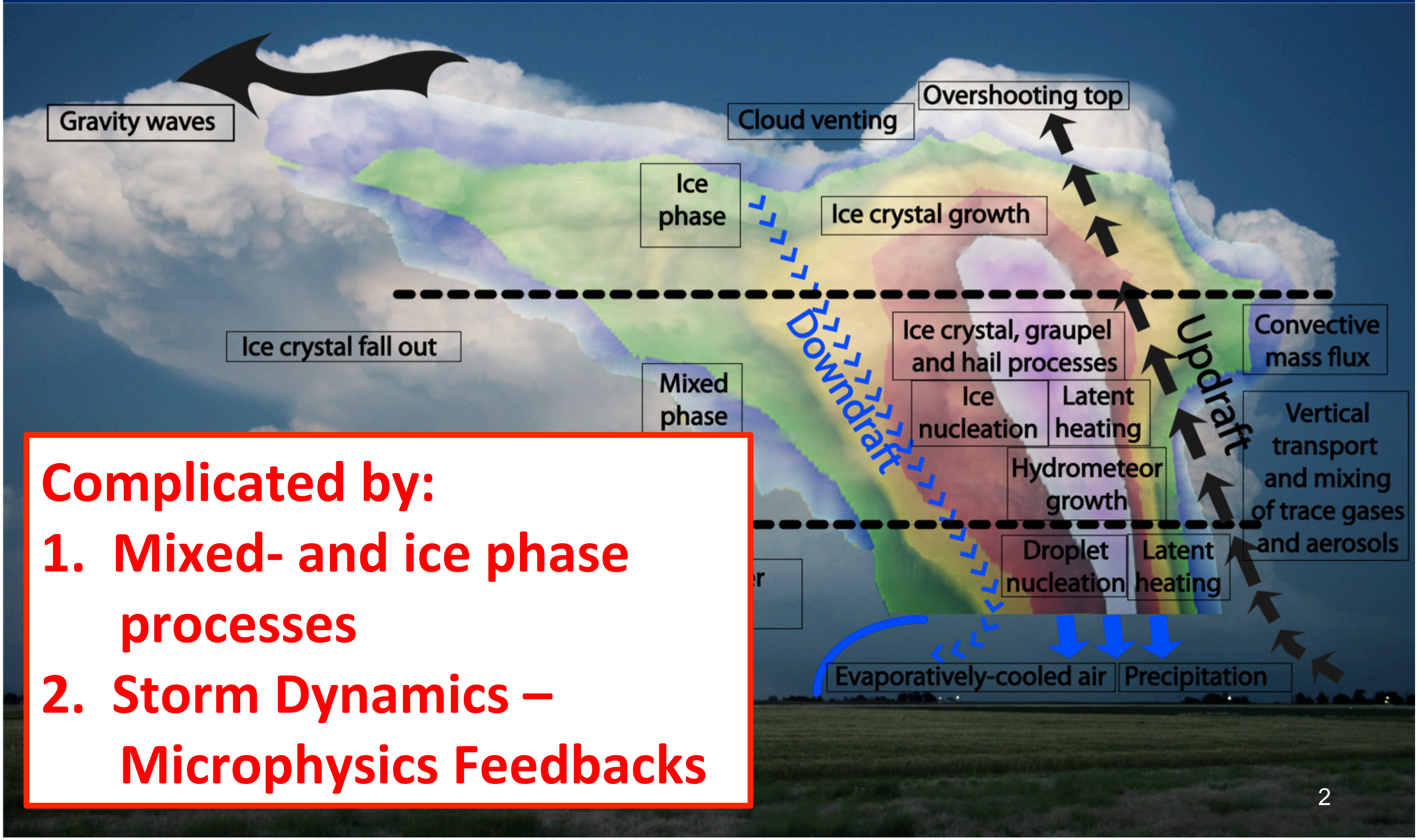
Colorado State University

Modified and Presented by

Zhanqing Li

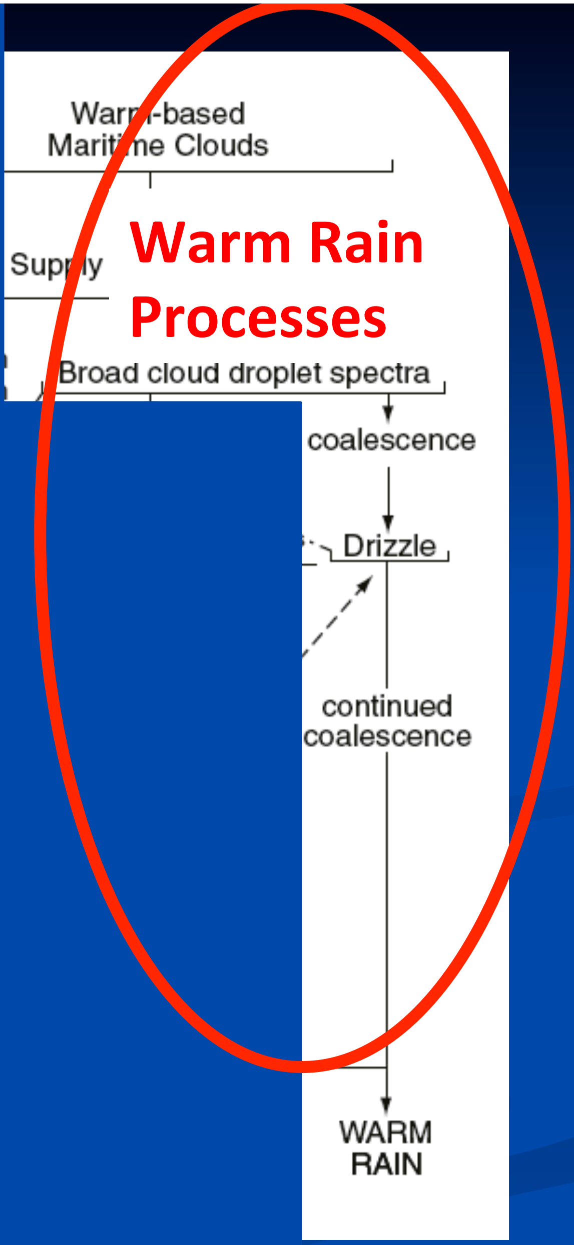
Aerosol Effects on Deep Convection



Complicated by:

1. **Mixed- and ice phase processes**
2. **Storm Dynamics – Microphysics Feedbacks**

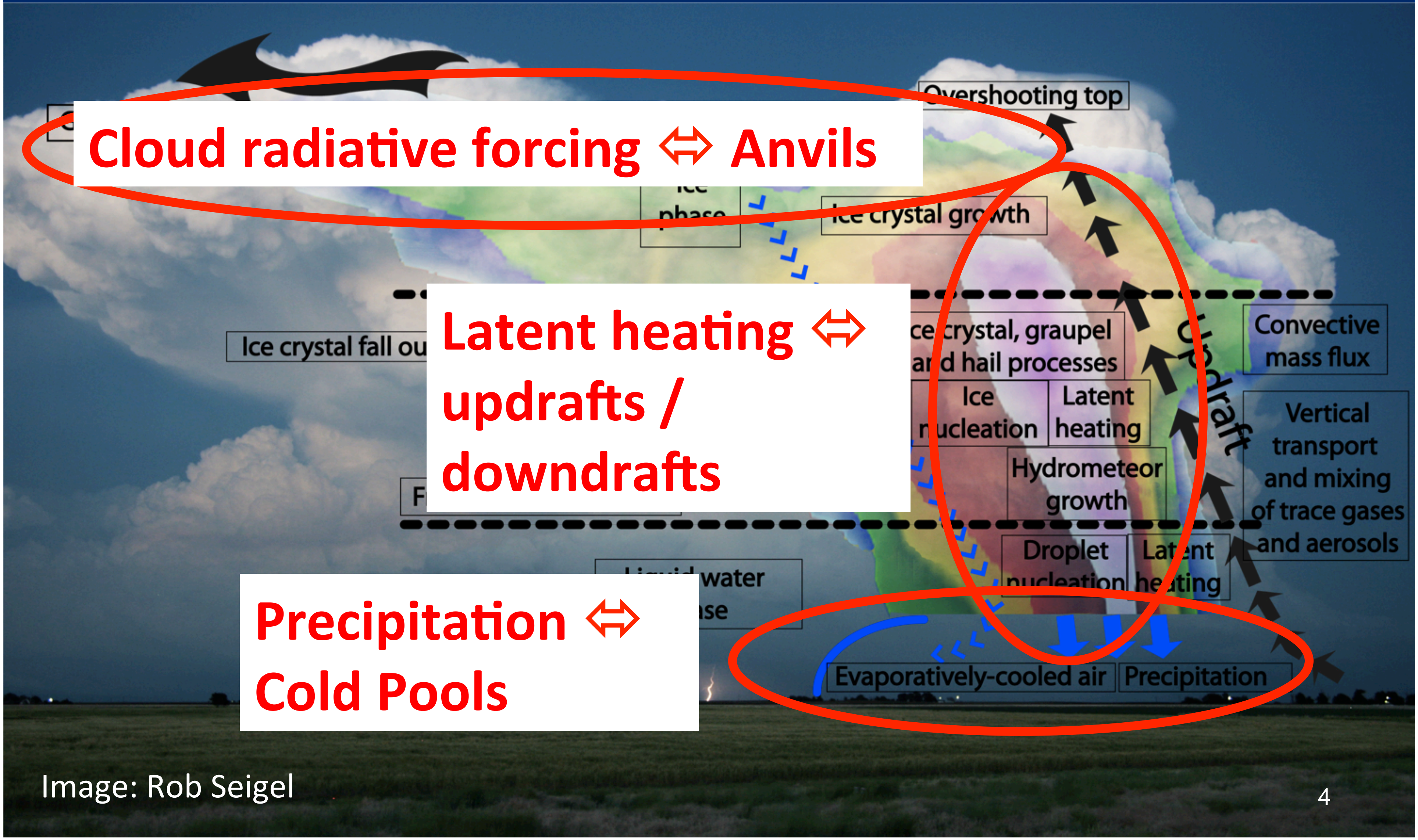
Mixed and Ice Phase Processes



Warm Rain Processes

Flow diagram showing microphysical processes and paths for precipitation formation (adapted from Braham (1968); after Cotton, Bryan and van den Heever, 2010)

Aerosol Effects on Deep Convection



Cloud radiative forcing ⇔ Anvils

Latent heating ⇔ updrafts / downdrafts

Precipitation ⇔ Cold Pools

Image: Rob Seigel

Question

- **What aerosol-related processes control deep convective cloud properties relevant to climate?**
- Cloud properties to be considered:

1. Latent heating profiles
2. Precipitation
3. Cloud radiative forcing

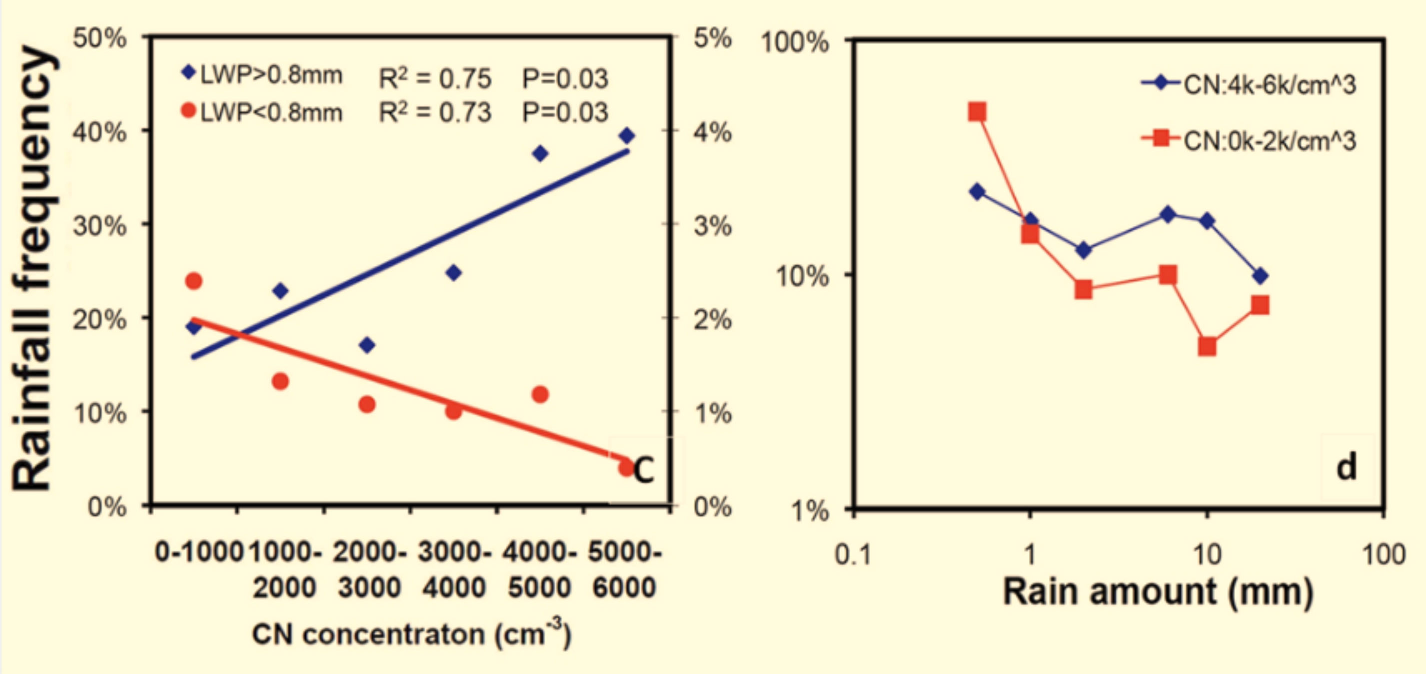
Uncertainties – Latent Heating

- Location and magnitude of latent heating significantly influenced by:
  - Mixed-phased microphysical processes
  - Vertical velocity
  - Feedbacks between latent heating and vertical motion

Uncertainties - Precipitation

- Precipitation
  - “Among these modeling studies, the most striking difference is that cumulative precipitation can either increase or decrease in response to higher concentrations of CCN.” (Tao et al 2012, Rev. of Geophy.)

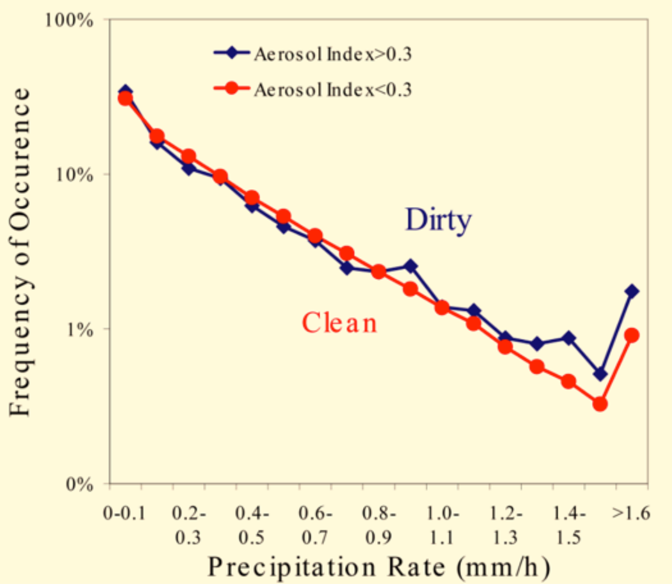
Changes in Rainfall Frequency to Increase of CN



From ARM Surface

Li et al. (2011, Nature-Geo)

From A-Train Satellite



Niu and Li (2012, ACP)

Uncertainties – Cloud Radiative Forcing

- Cloud radiative forcing
  - Responses vary from negative in many previous climate modeling studies (even when aerosol impacts on deep convection are included) through to positive responses in recent observational, CRM and conceptual studies

1. Seasonal and Regional Responses

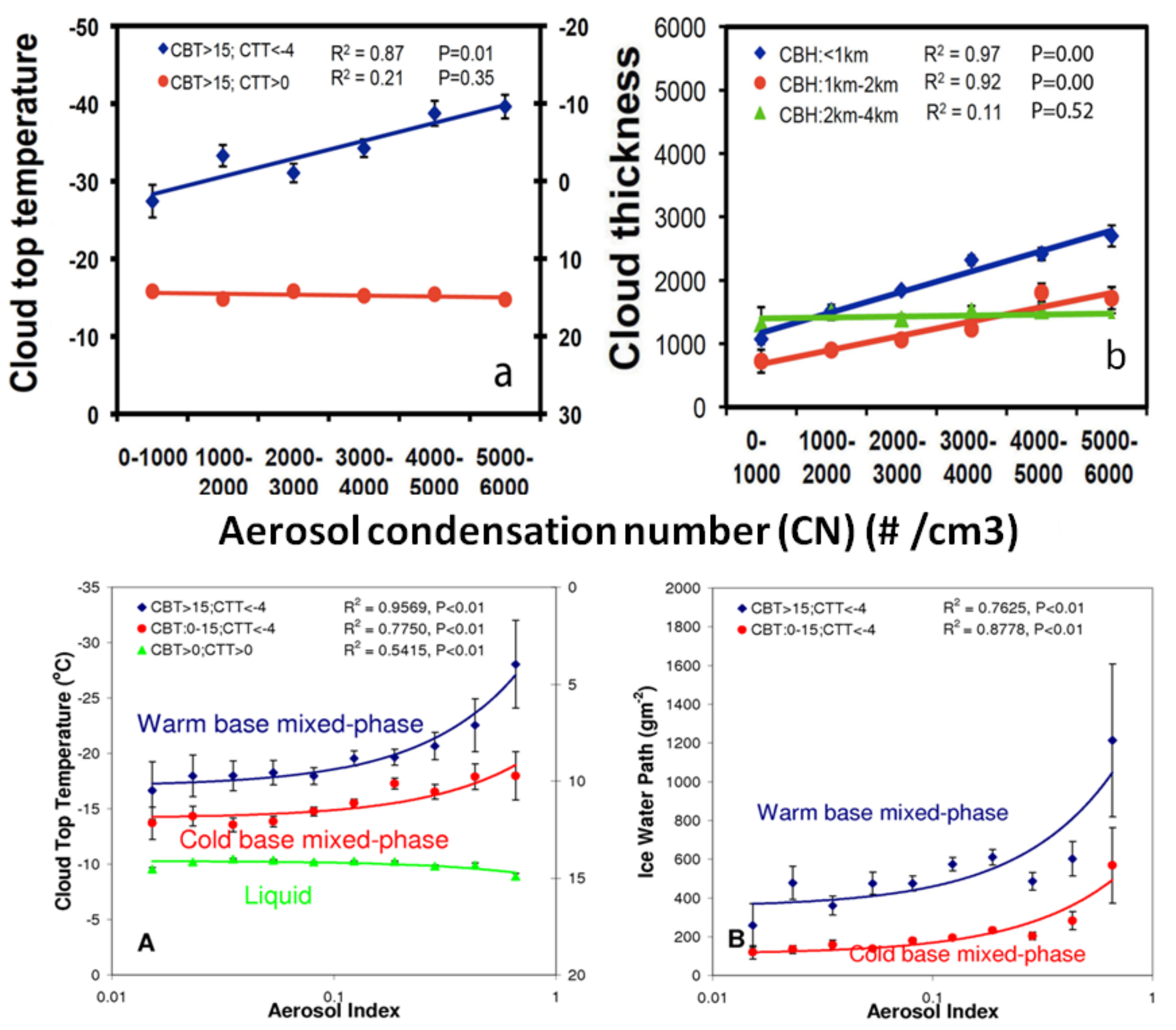
Questions

- Many early observational and modeling studies of aerosol indirect effects on DC focused on single events, isolated single-cell storms and specific environments
- Are effects on updrafts, latent heating and precipitation consistent on large spatial and temporal scales under a range of environments or is this a short-lived, isolated response?

Recent Observational Studies

- MODIS – evidence of systematic invigoration of convective clouds under polluted environments (Koren et al. 2005)
- ARM ground (10 years) and A-Train satellite (trpics) data (Li et al 2011; Niu and Li 2012) – strong climatic effects of aerosols on clouds & precipitation
- Observed intensification of rain rates from the tropics to the midlatitudes (Koren et al 2012)

Long-term and Global Signals of ADCI



10-year ARM ground data

(Li et al. 2011 Nature-Geosci)

1-year satellite data in tropics

(Niu and Li 2012 ACP)

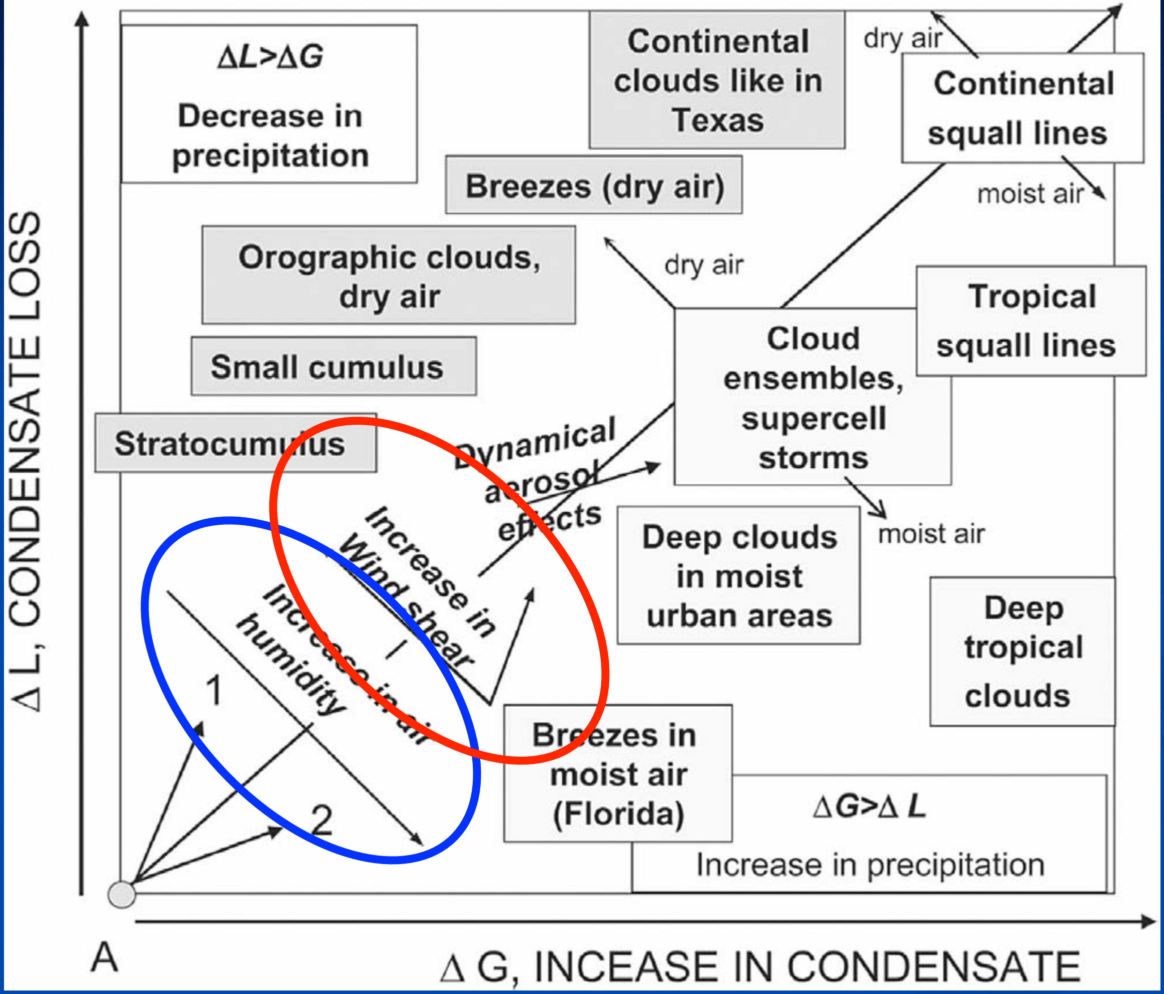
2. Role of Environment

Questions

- Do aerosol indirect effects on latent heating, updrafts and precipitation vary with different environments?
- Are there environmental thresholds above which we don't need to worry about aerosol indirect effects?
- Are some environmental factors more important than others?

Relative Humidity and Wind Shear

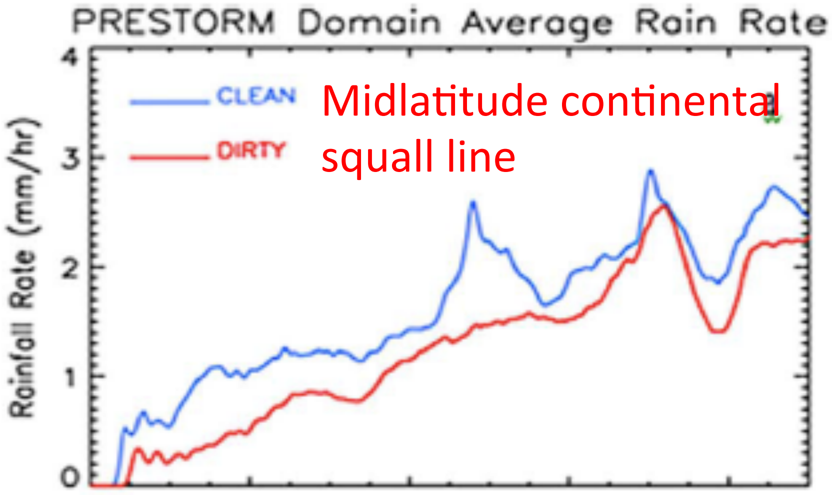
Precipitation Decrease



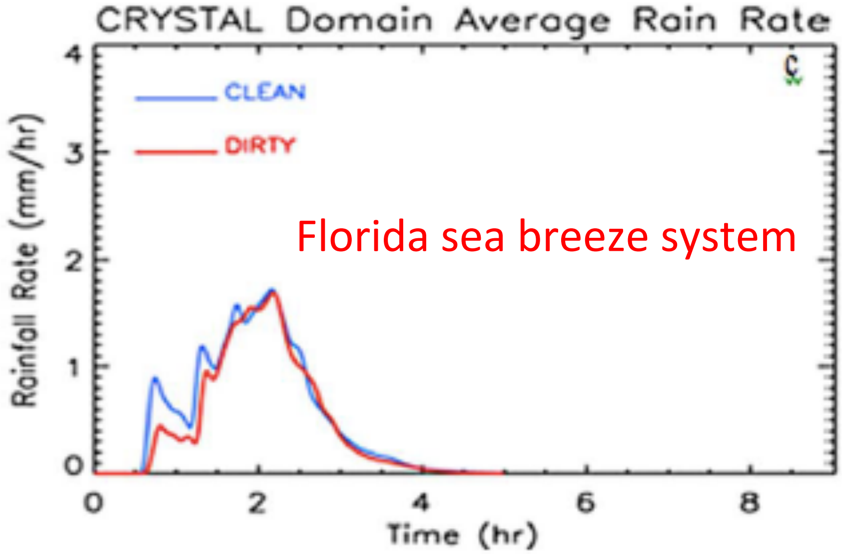
Precipitation Increase

Schematic showing aerosol effects on clouds and cloud systems of different types. Below the diagonal, precipitation increases with increasing aerosol concentrations. Above the diagonal precipitation decreases with increasing aerosol concentrations (after Khain et al. 2008)

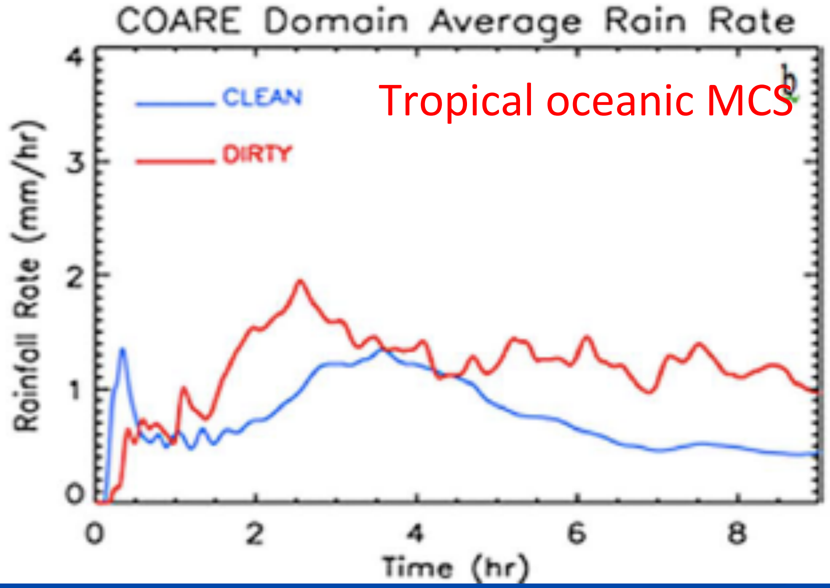
Precipitation - Different Environments



Midlatitude continental squall line



Florida sea breeze system



Tropical oceanic MCS

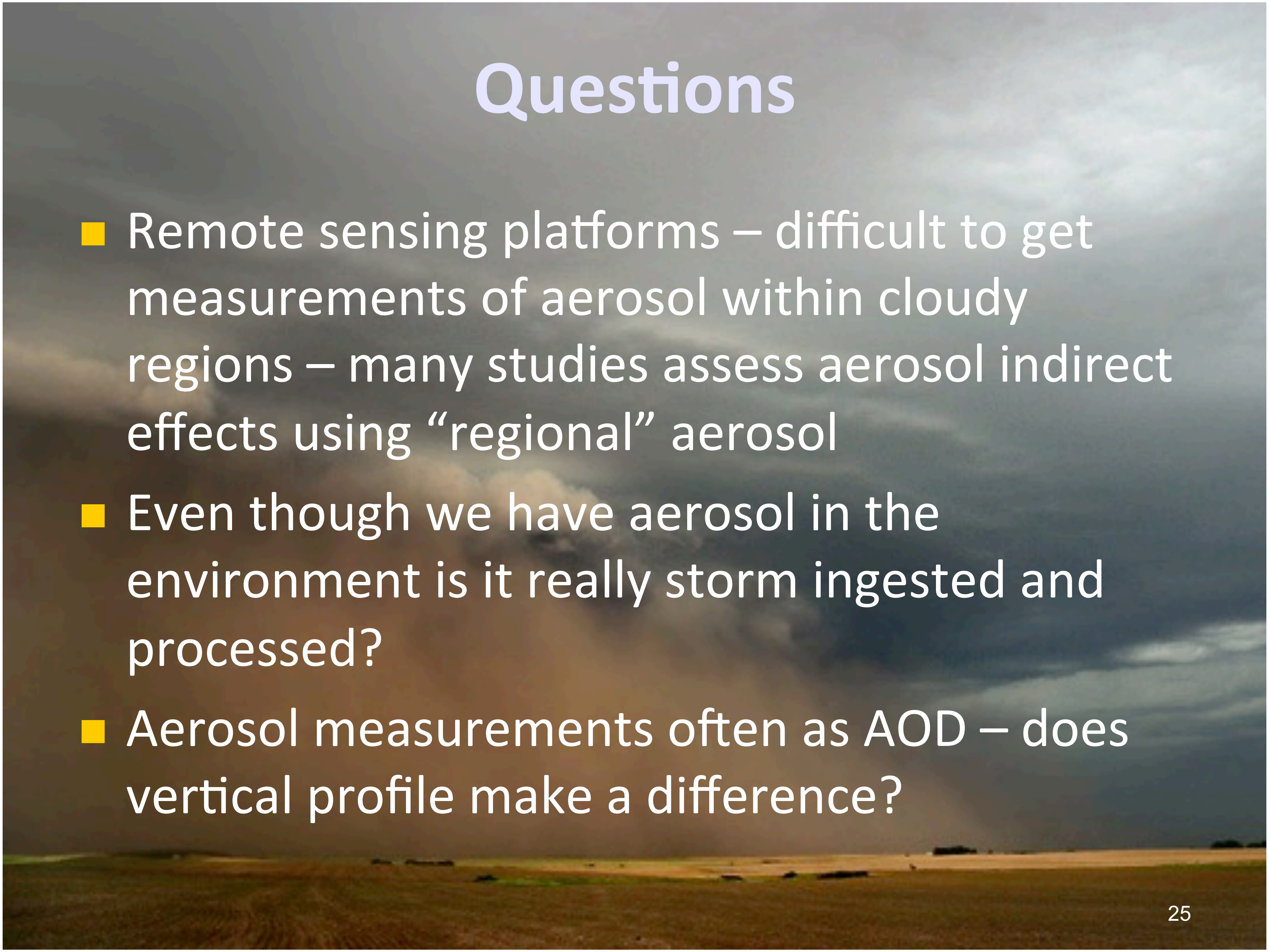
Time sequences of surface rainfall rates for clean and polluted conditions for a variety of storm types and conditions (after Tao et al 2007)

Aerosol Impacts and Vertical Wind Shear

- Weak shear => aerosol-induced invigoration, strong radiative warming, lofted latent heating, reduced diurnal temperature differences (Fan et al 2009; 2012)
- Strong shear – reduced convection
- Impacts on downdraft strength and subsequent convergence and convection (Lee et al. 2008)

3. Importance of Vertical Location

- Some studies have stressed the importance of BL aerosol (van den Heever et al 2006)
- Others have shown the importance of aerosols between 6 and 10km on deep convective anvil characteristics (Fridland et al 2004)
- Does level of ingestion impact activation?
- Very little research has been conducted in this area



Questions

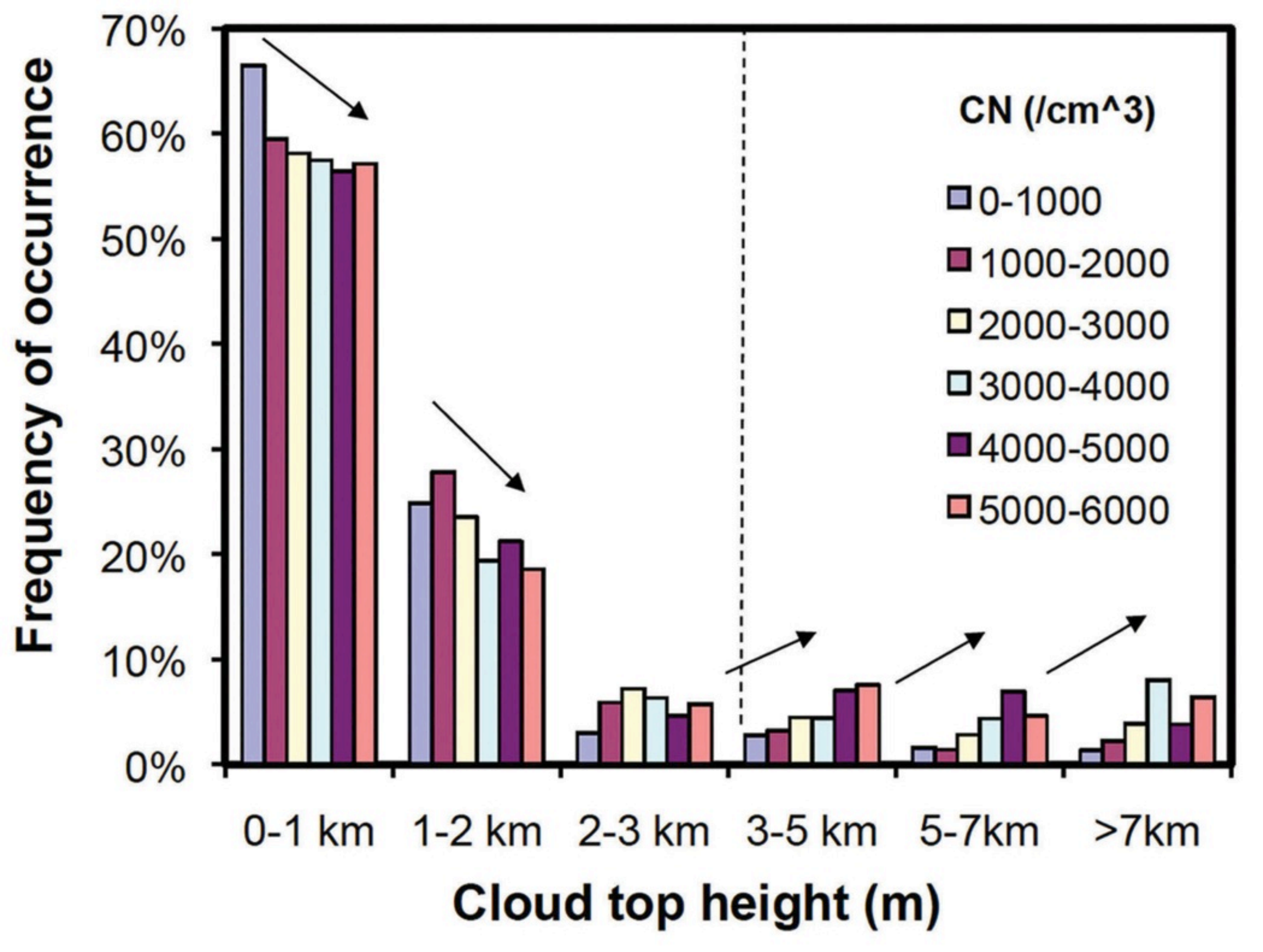
- Remote sensing platforms – difficult to get measurements of aerosol within cloudy regions – many studies assess aerosol indirect effects using “regional” aerosol
- Even though we have aerosol in the environment is it really storm ingested and processed?
- Aerosol measurements often as AOD – does vertical profile make a difference?

4. Life Cycle

Questions

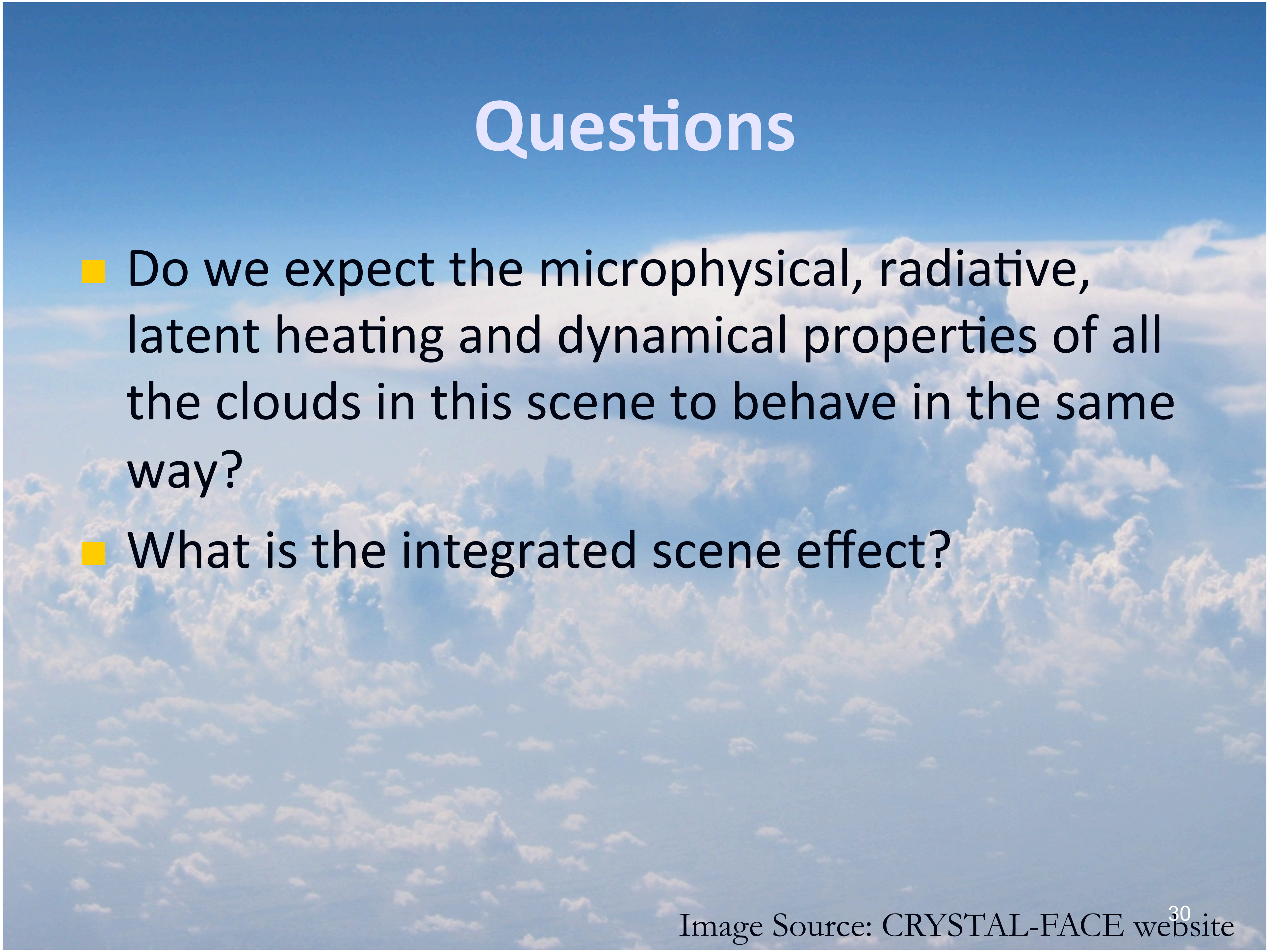
- Do aerosol indirect effects impact storm characteristics differently depending on the stage in the life cycle?
- Are they more important initially or during the mature stage?
- Can the entire life cycle be characterized by the same response?

Frequency of Occurrence does differ for low (initial) than for high (mature) clouds



Li et al. (2011)

5. System-Wide Response



Questions

- Do we expect the microphysical, radiative, latent heating and dynamical properties of all the clouds in this scene to behave in the same way?
- What is the integrated scene effect?

Image Source: CRYSTAL-FACE website

Variations by Cloud Type

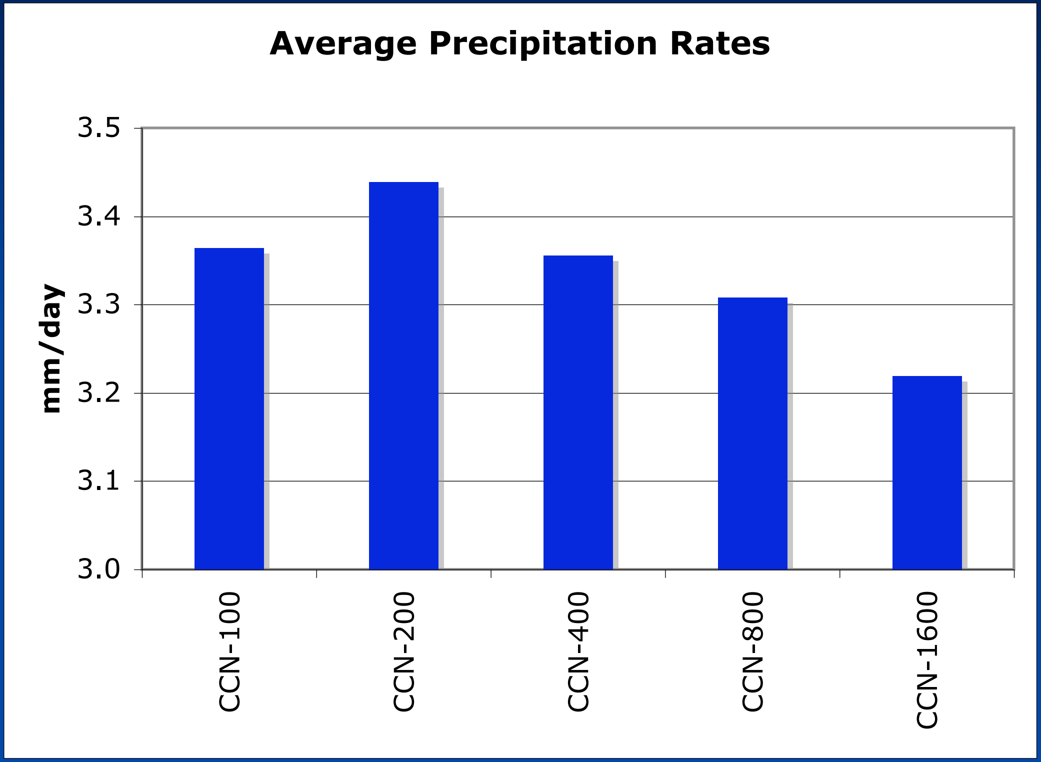
- Seifert and Beheng (2006, JGR)
  - Variations in response by cloud type
  - Negative precipitation response for ordinary cells and supercells but positive response for multicells
- Khain et al (2008, JAS)
  - Decrease in precipitation typically for isolated clouds in dry conditions

Precipitation Contribution (%) by Cloud Regime

Cloud Type	CCN-100	CCN-200	CCN-400	CCN-800	CCN-1600	
Shallow	12.3	10.8	9.4	6.9	4.8	↓
Congestus	9.3	8.6	8.8	9.0	9.7	↓ ↑
Deep	78.4	80.5	81.7	84.0	85.4	↑

Contributions to total precipitation by cloud mode as a function of aerosol concentration (after van den Heever et al 2011)

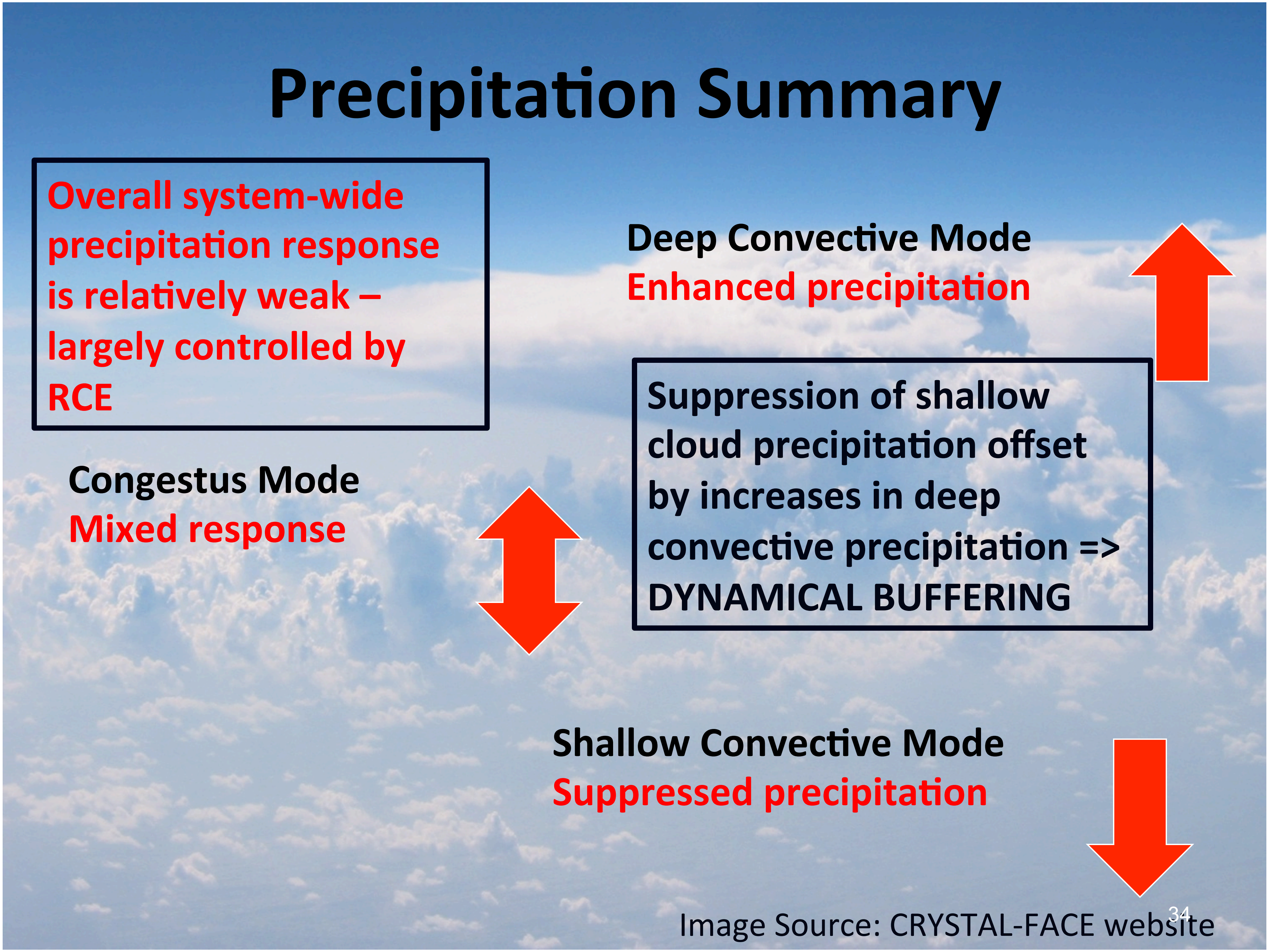
Domain-Wide Precipitation Rates



- Averages are comparable to those observed in the Tropics
- Enhanced CCN
  - Slight decrease in surface precipitation rates

Temporally (40 days) and horizontally-averaged precipitation rates over entire model domain as a function of CCN concentration

Precipitation Summary



Overall system-wide precipitation response is relatively weak – largely controlled by RCE

Deep Convective Mode

Enhanced precipitation

Suppression of shallow cloud precipitation offset by increases in deep convective precipitation => DYNAMICAL BUFFERING

Congestus Mode

Mixed response

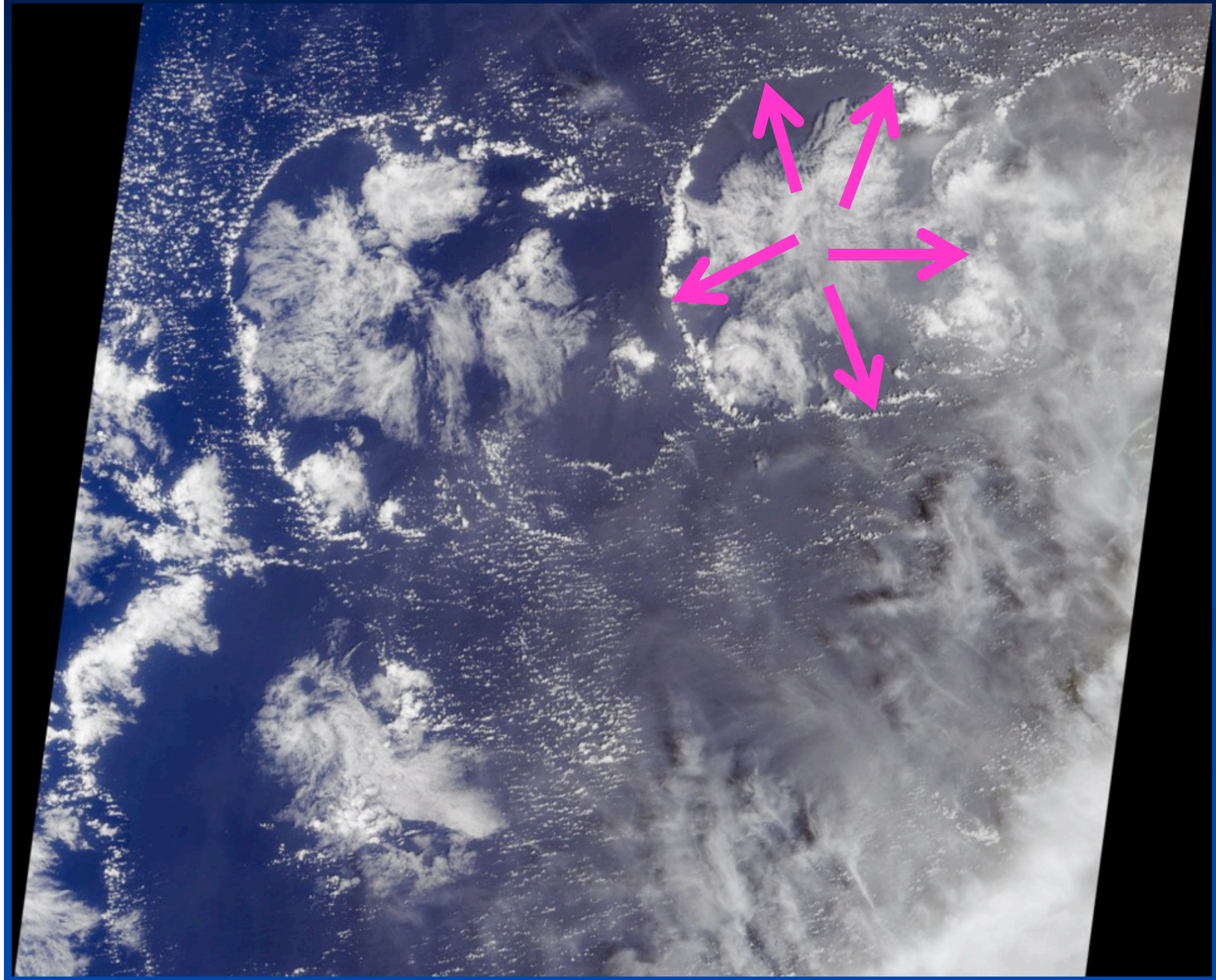
Shallow Convective Mode

Suppressed precipitation

Image Source: CRYSTAL-FACE website

7. Cold Pools and Secondary Convection

Cold Pools



Satellite imagery of ocean tropical cold pools and their associated outflow boundaries (Image courtesy of NASA/GSFC/LaRC/JPL, MISR Team)

- Organized and isolated deep convection fundamentally dependent on interaction with evaporatively-generated cold pool and its co-location with the updraft

Questions

- Are evaporatively-generated cold pools warmer or colder under polluted conditions?
- Do we see changes to the vertical structure of latent cooling?
- Are parent updrafts stronger and longer-lived?
- Secondary convection?
- Is this a local effect or does it have larger scale implications?

8. Convective Anvils – Cloud Radiative Forcing

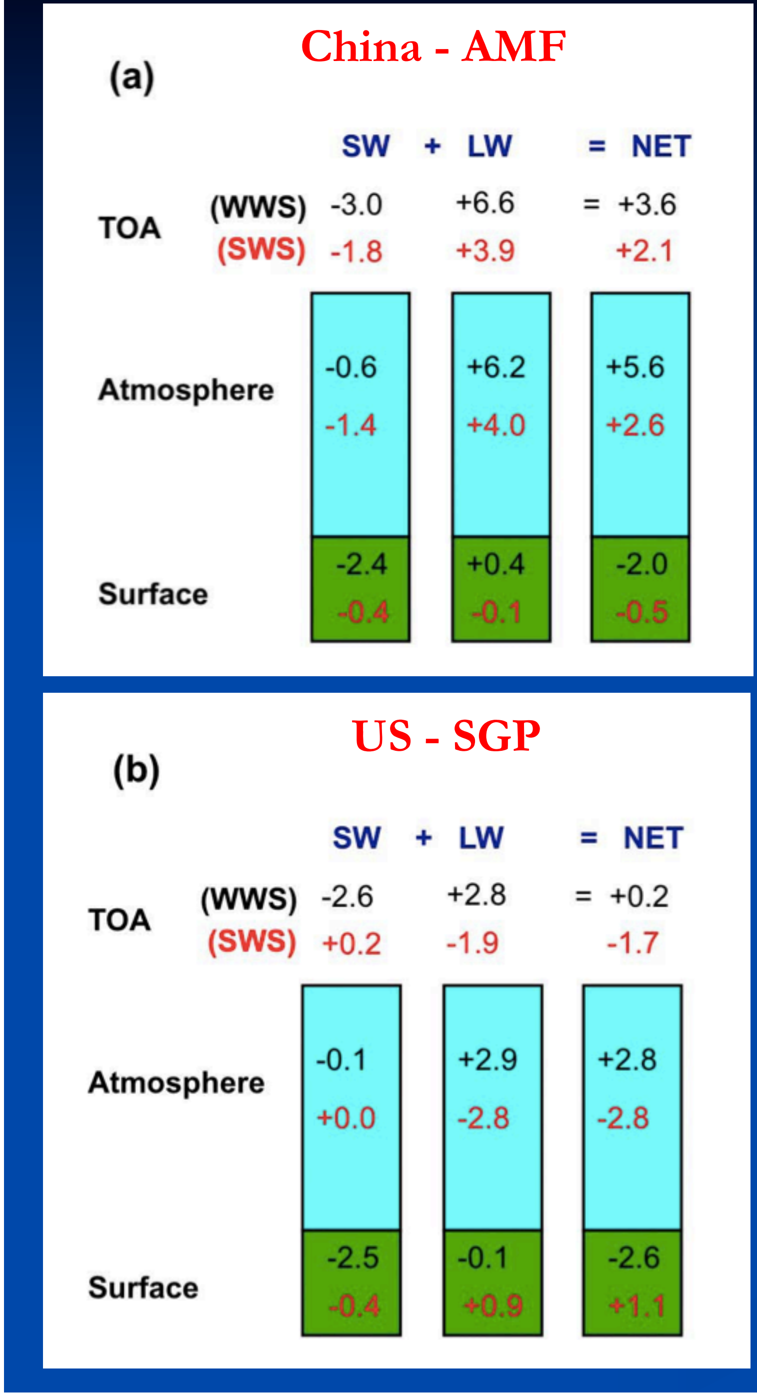
Cloud Radiative Forcing

- Previous climate modeling studies => aerosol indirect forcing is negative even when the interactions between aerosols and deep convective clouds are included in a simple framework (Lohmann et al 2010; Quaas et al 2009)
- Observational analysis (Koren et al 2010) and conceptual models (Rosenfeld et al 2008) suggest that warming can occur at the TOA as a result of invigorated convection and expanded anvils
- We are evaluating the clamatological values using multi-year of satellite data.

Questions

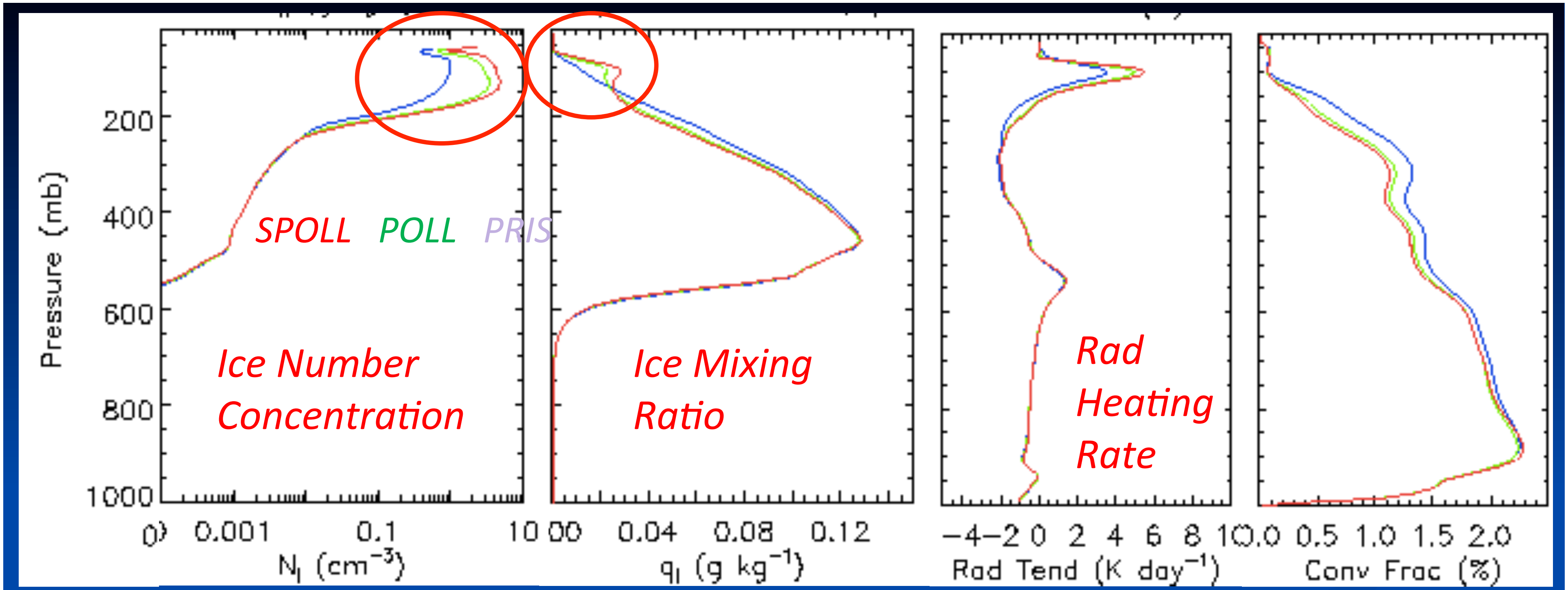
- Does aerosol indirect forcing produce warming or cooling at cloud top?

Radiative Forcing



- Radiative forcing relatively significant when aerosol induced invigoration is significant
- Occurs in cases with weak shear
- Strong shear can cause reverse (cooling) at TOA and atmosphere

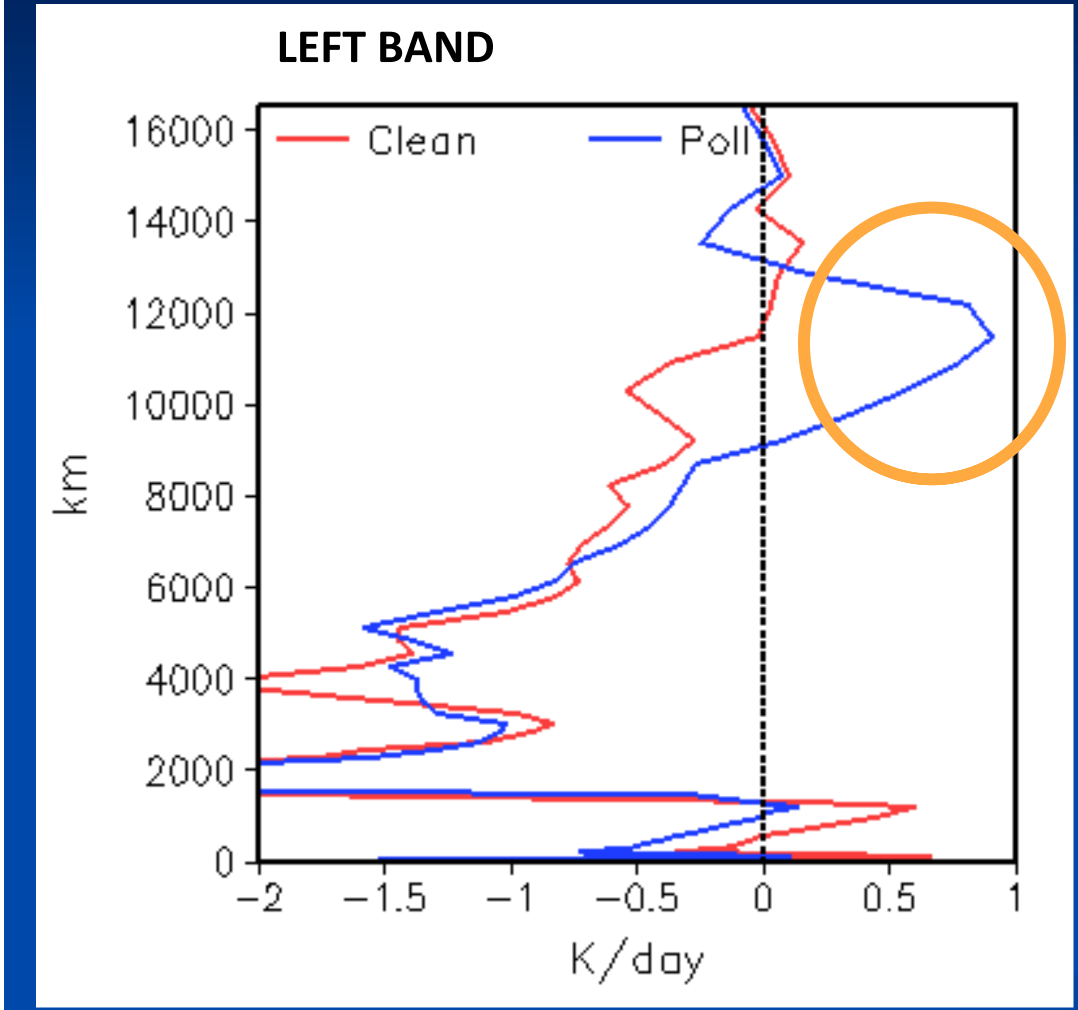
SW, LW and net radiative forcing of aerosol indirect effects at the TOA, atmosphere and surface for the (a) China and (b) SGP cases. Values in red are for stronger shear conditions. Values represent a 24 hour average (after Fan et al 2012)



- Model produces a small increase in anvil thickness/height in polluted conditions consistent with some observations (Massie et al. 2011).
- This does *not* occur due to convective invigoration, but rather is a direct result of changes in ice number concentration due to higher concentration of droplets in polluted conditions and their subsequent freezing.
- These results suggest a possible alternative to convective invigoration in explaining small increases anvil height/thickness suggested by satellite.

(after Morrison and Grabowski 2011; Slide provided by Hugh Morrison)

RCE Results => Initial Radiative Heating Rate



- Greater upper-level radiative heating
- In association with greater upper-level condensate mass and increasing cloud fraction
- Reduced instability => important impacts on subsequent convection

Radiative heating rates for the clean and polluted bands (after van den Heever et al 2012)

9. Aerosol Type

Questions

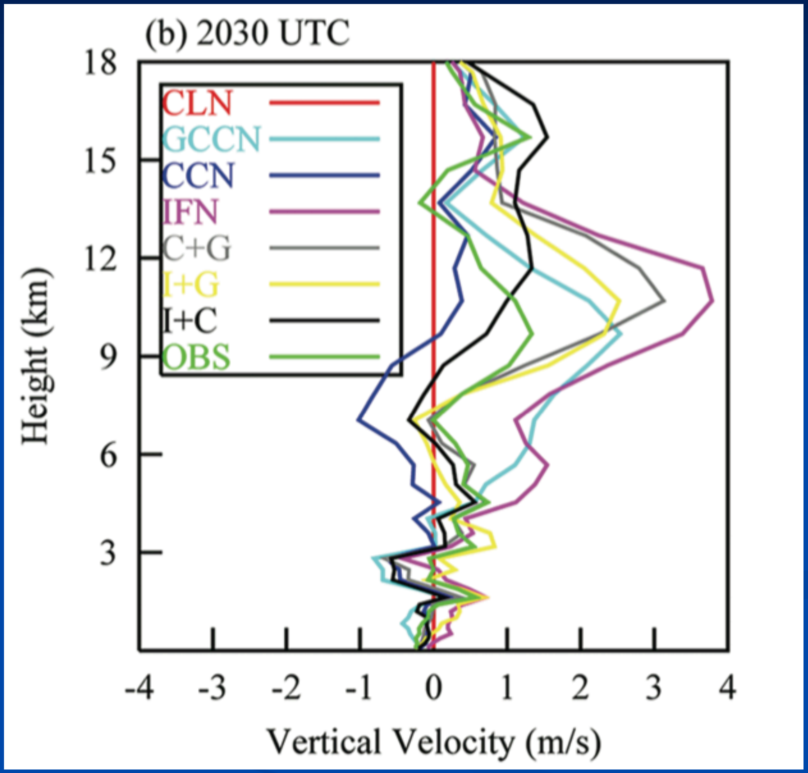
- Impacts of aerosol operating as CCN been primary focus
- Very few studies on the impacts of GCCN and IN on precipitation processes => primarily due to our lack of observations and understanding of IN and ice processes in general
- Do aerosol impacts on latent heating, precipitation and cloud radiative forcing vary with aerosol type?

IN

- Ekman et al (2007) => enhanced IN => enhanced heterogeneous nucleation => more latent heat release => stronger updrafts => more homogeneous nucleation and enhanced impact of CCN on cloud properties => impacts on particle concentrations, anvil size and radiation.
- Similar results obtained observationally by Heymsfield et al (2005)
- Fan et al (2010) => impacts of IN on tropical deep convection => increase in immersion nucleation rate => stronger convection, larger anvils and longer anvil lifetime

CCN vs IN

- IN => greatest impacts on anvil dynamics
- CCN and/or GCCN more dominant in warmer rain regions
- Combinations effective in mixed-phase regions



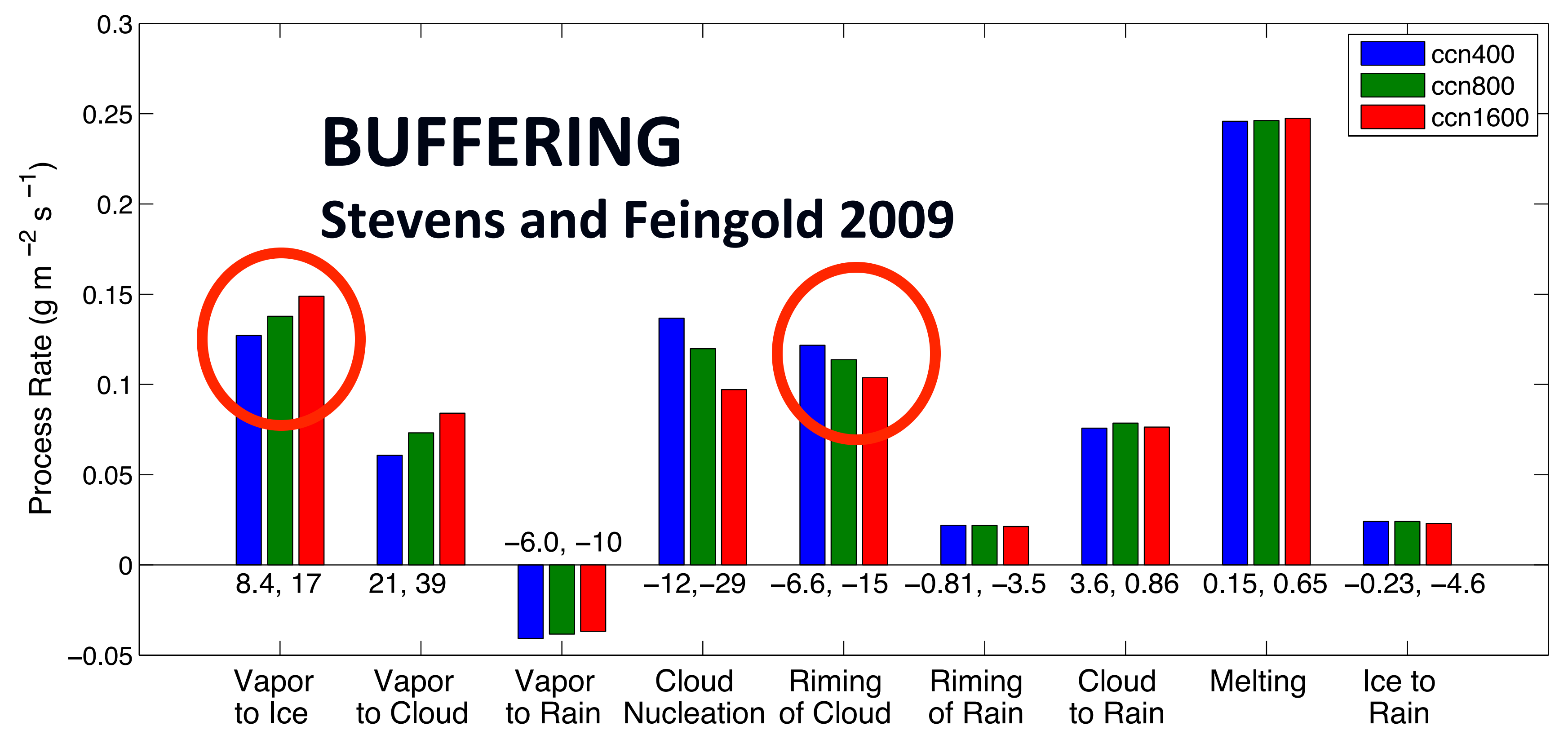
Vertical profiles of the difference of the sensitivity experiments and the CLN case for the horizontally-averaged vertical velocity within the convective cores for the mature stage (van den Heever et al. 2006)

10. Microphysical Processes

Questions

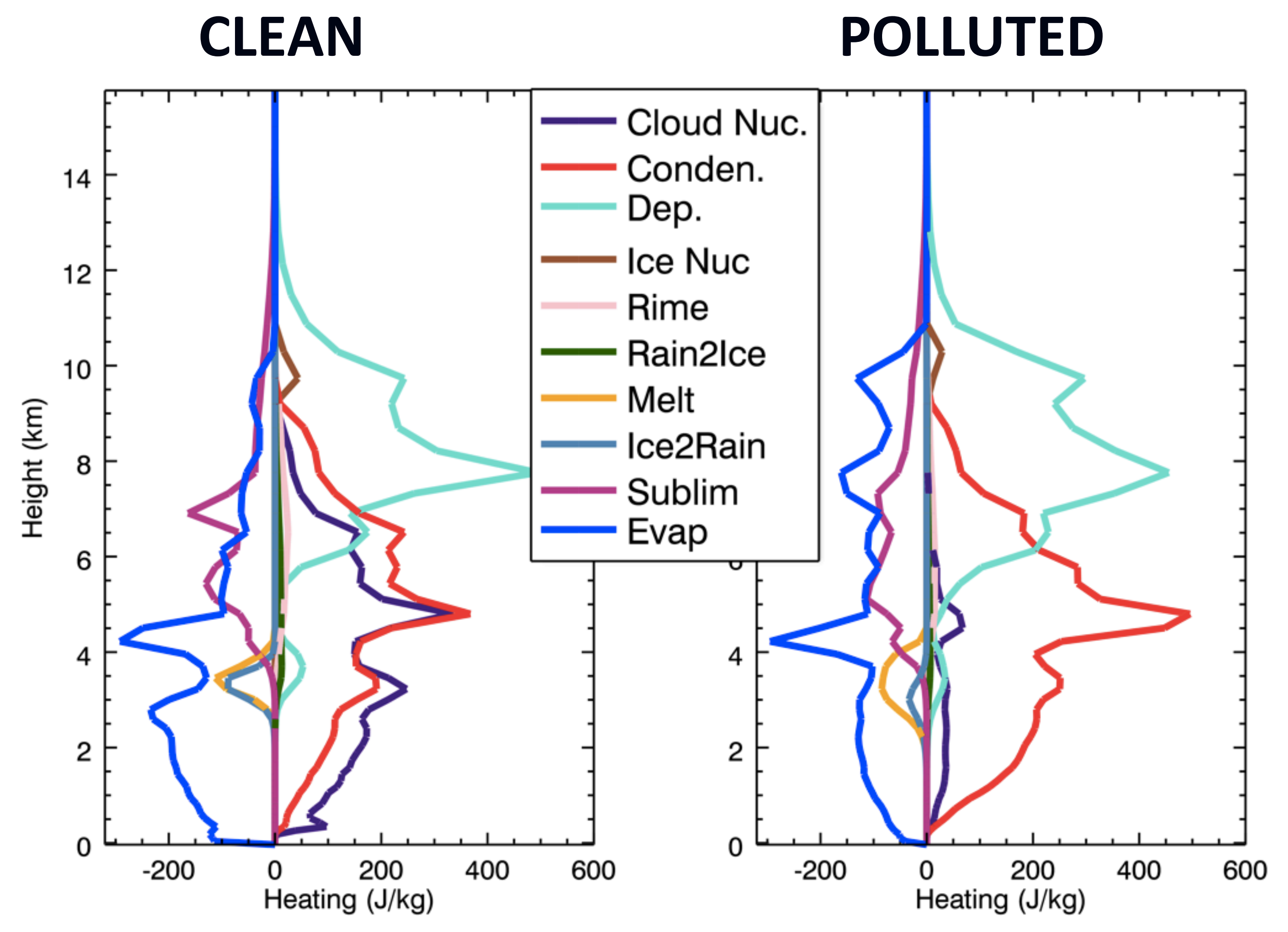
- Are there some microphysical processes that are more susceptible to aerosol indirect forcing than others?
- If so, which process(es) should we be focusing on improving in our models?
- Do some aerosol-induced processes offset other aerosol-induced processes?
- Should we not be focusing first on improving our representation of ice processes in models before being concerned more specifically about IN?

Buffering



Vertically integrated and averaged rates of each of the major water budget processes. The two numbers printed with each process are the percent change of CCN800 and CCN1600, respectively, from the CCN400 value (after Igel et al 2012)

Microphysical Processes ⇔ LH

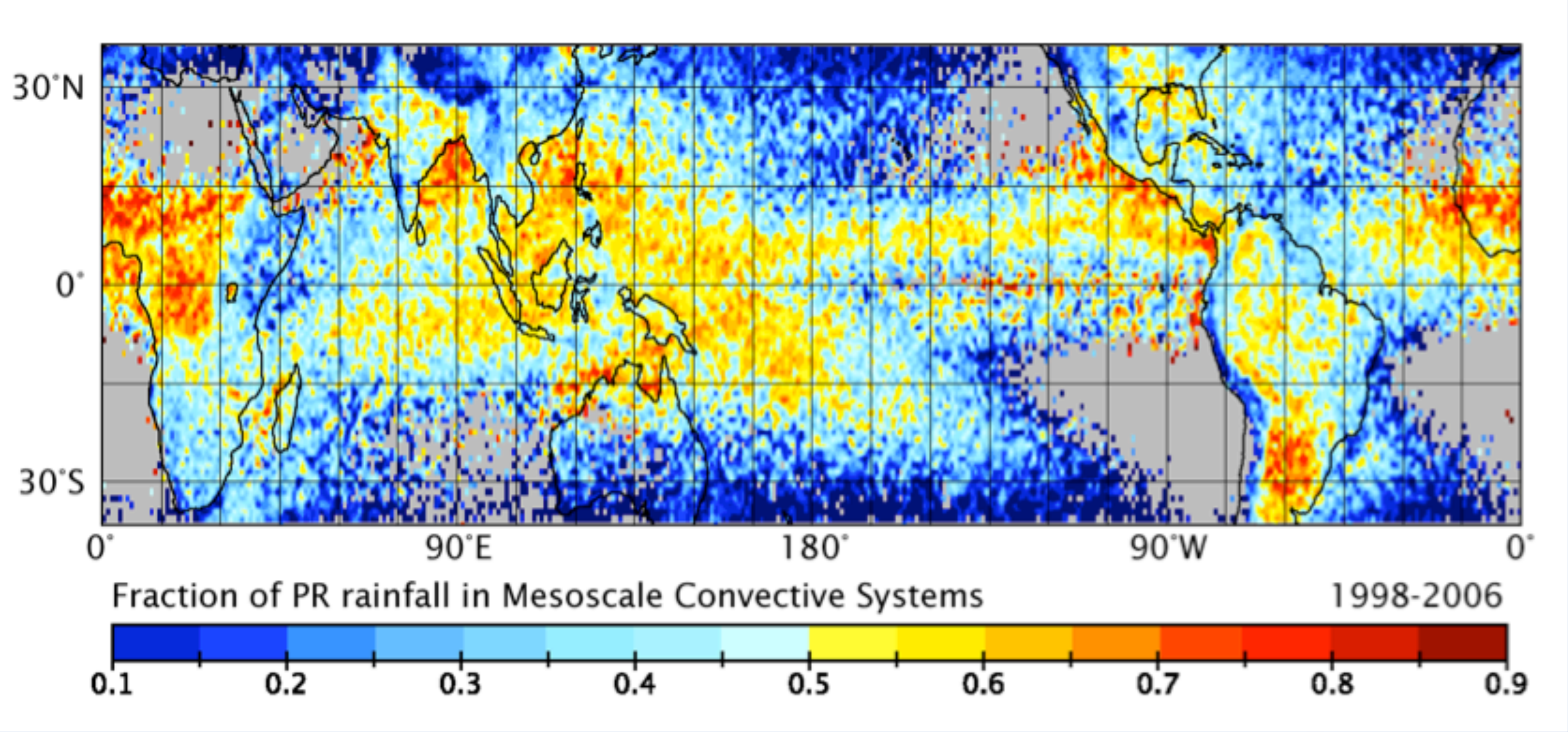


- How do we verify such results?

Microphyiscal processes leading to latent heat release in clean and polluted conditions (after Storer and van den Heever 2012)

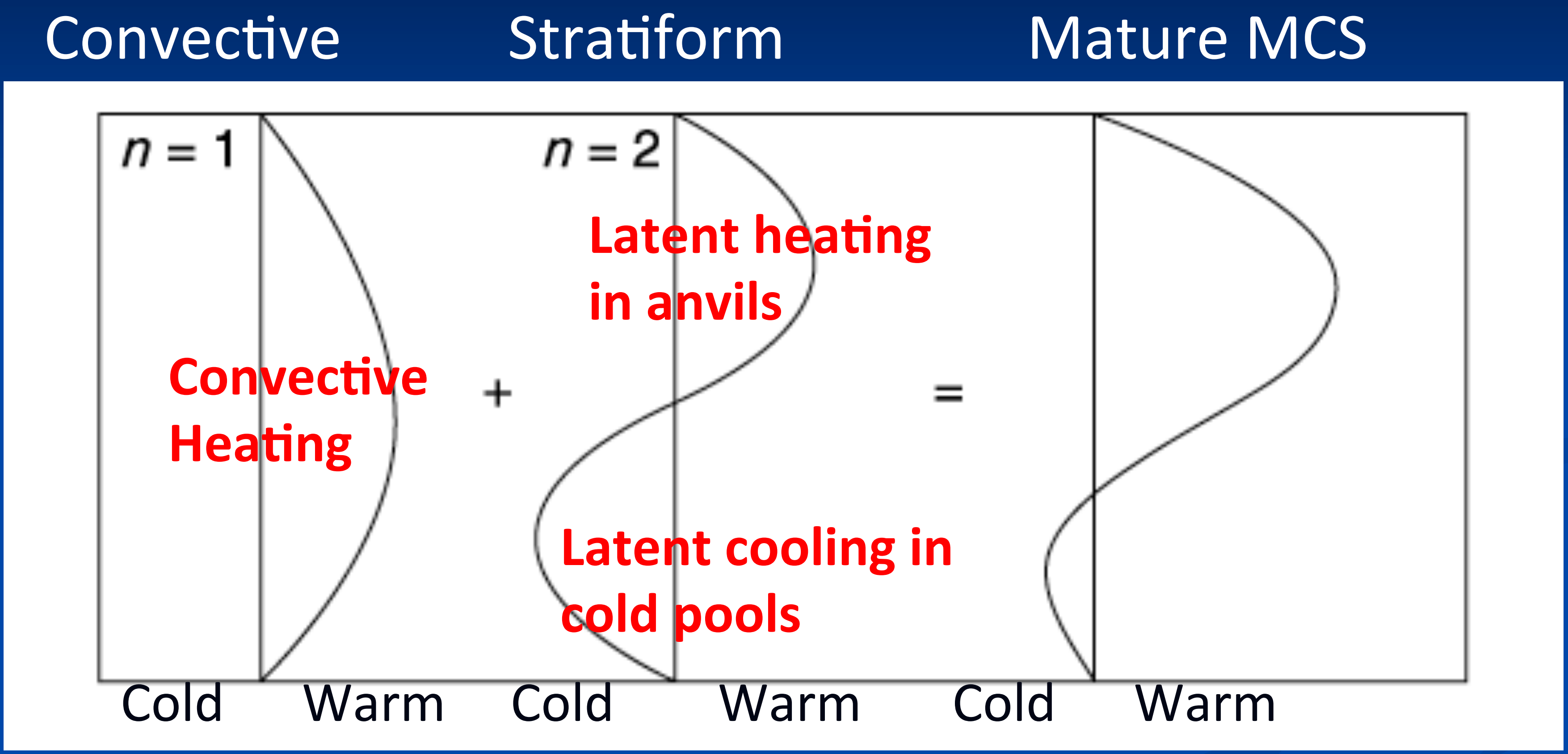
11. Organized Convection

MCS Contribution to Tropical Rainfall



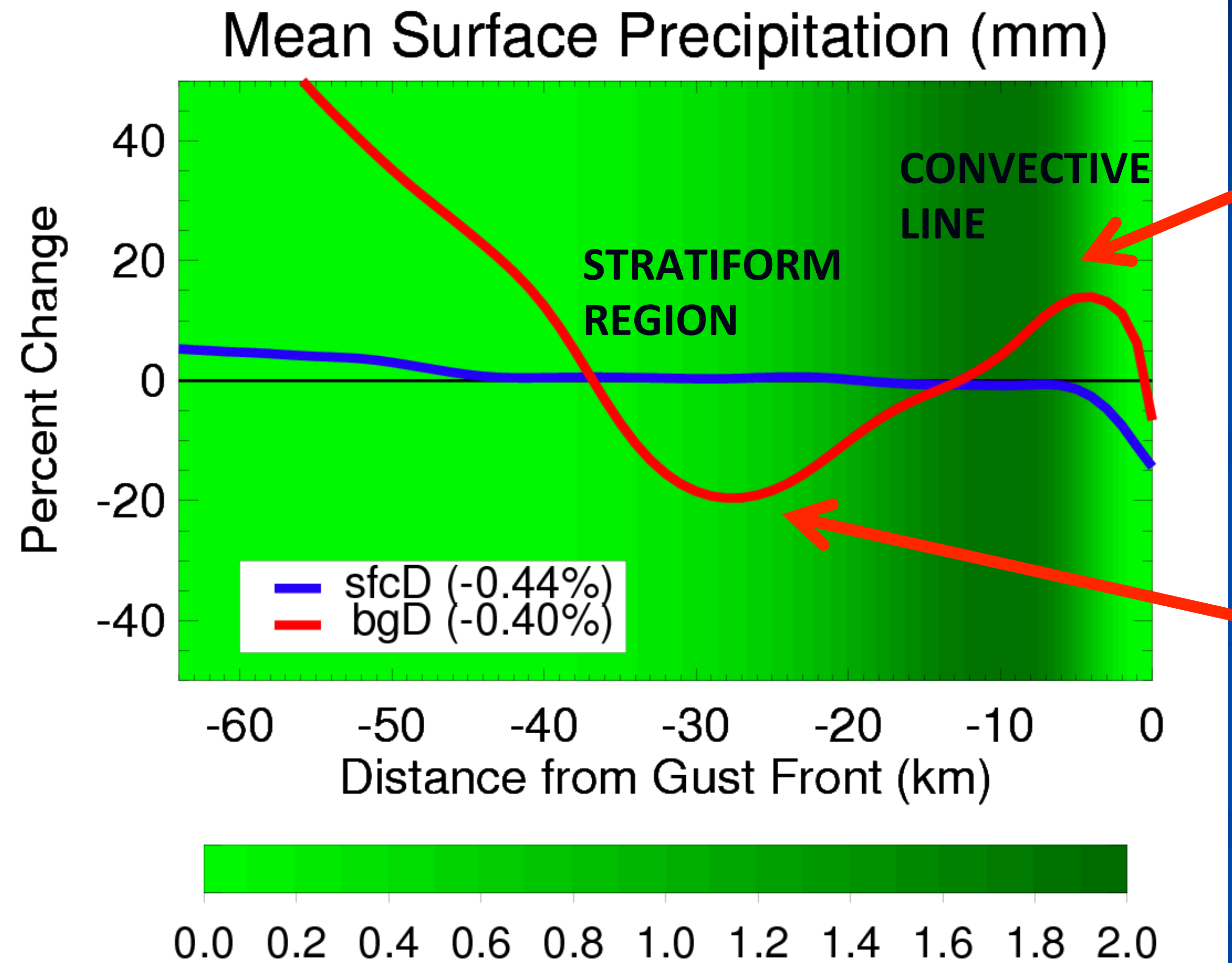
The contribution (%) of MCSs to tropical rainfall totals (after Nesbitt et al 2006)

MCS Contribution to Latent Heating



Latent heating profiles associated with the convective and stratiform regions of MCS (From Nicholls et al 1991)

Aerosol Impacts on Convective and Stratiform Precipitation



Enhanced precipitation in convective line

Reduced precipitation in stratiform region

(after Seigel et al 2012)

Strawman – Requirement 1

- **Measurements of vertical velocity through the depth of deep convective systems:**

1. Co-located measurements of in-cloud aerosol (including concentrations, type, vertical profiles) – not just regional aerosol
2. As a function of environmental characteristics
3. Throughout storm life cycle
4. For isolated and organized storms
5. Co-located radiation profiles
6. Key element in LH calculations

Strawman – Requirement 2

- **System-wide responses to varying aerosol concentrations:**

1. Support of satellite platforms and initiatives
2. Ground validation
3. Range of different environments and regions of the world
4. Temporally and spatially assessed AND integrated area response

Strawman – Requirement 3

- **Improve understanding of mixed and ice processes and hence their representation in cloud resolving through global models:**

1. Better measurements of IN
2. Particles that can serve as CCN and IN
3. Ice nucleation processes
4. Secondary ice production
5. Processes involving snow crystals and aggregates through graupel and hail

Strawman – Requirement 4

- **Impacts on organized convective systems**

1. Local and storm-wide measurements
2. Local impacts such as on the convective line => important short-term forecasting implications in changing climates (flooding etc)
3. Integrated effect – over whole storm and entire lifetime => important climate effect (latent heating profiles, cloud radiative forcing)

Potential Approach

- **Several other field campaigns similar to GoAmazon2014 BUT:**

1. Extended to other regions: Eastern Atlantic, East coast of China and the Sahara
2. Spatially and temporally frequent measurements of vertical velocity
3. In-cloud aerosol concentrations and type
4. Storm type and storm life cycle
5. Ice processes
6. Integrated spatially and temporally

General Recommendations

Requirement 5: Intertwining Observing & Modeling AIE (1)

- **From Observations:**

1. To exploit extensive measurements from ground-based (all ARM fixed sites and AMF sites), air-borne (ARM campaigns) and space-borne measurements to attempt to identify and quantify different types of AIEs
2. to provide metrics of the estimates of AIEs from a variety of observation platforms for validation and improvement of a hierarchy of models

Requirement 5: Intertwining Observing & Modeling AIE (2)

- **From Models:**

1. To run LES, CRM, SCM and GCM models to try to simulate observed cloud scenes with right aerosol inputs and meteorological settings.
2. To analyze modeled quantities in the similar manner as the analyses of observations to examine various relationships as revealed from observations concerning different types of AIEs.

Requirement 5: Intertwining Observing & Modeling AIE (3)

- Comparing observed and simulated relationships, we can:

1. Identify deficiencies in both modeling and observations regarding their validity in studying the AIE.
2. Sort out true effects from false appearance.
3. Evaluation of model's performance in simulating the AIEs from local to global scales
4. Recommendations for future improvements