Effect of aerosol on instability and convective clouds

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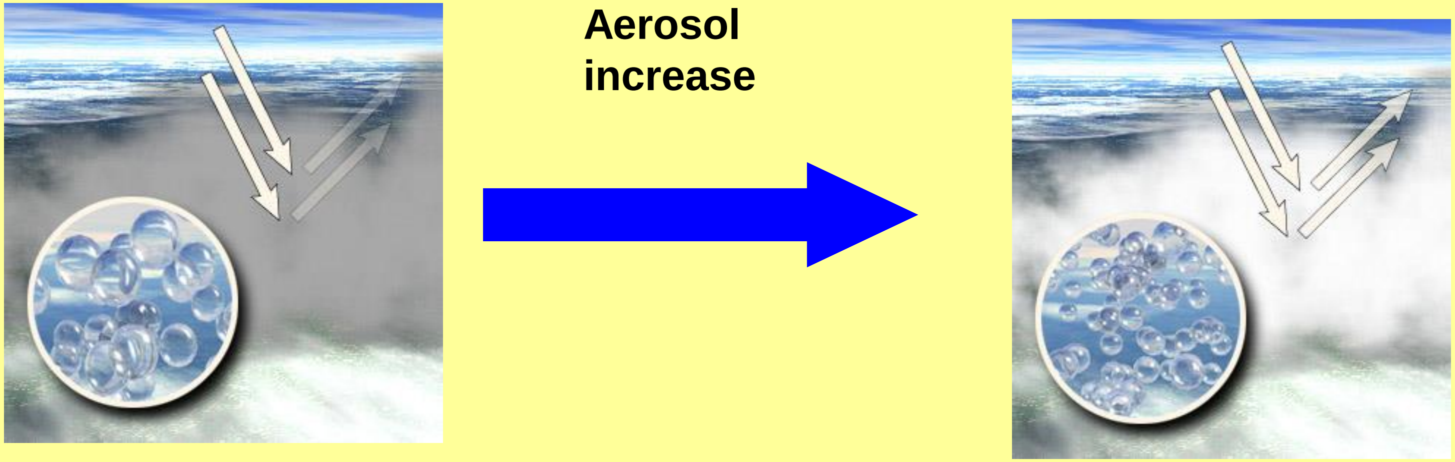
Introduction

- There has been an increase in aerosol concentrations since industrialization, decreasing the cloud-particle size

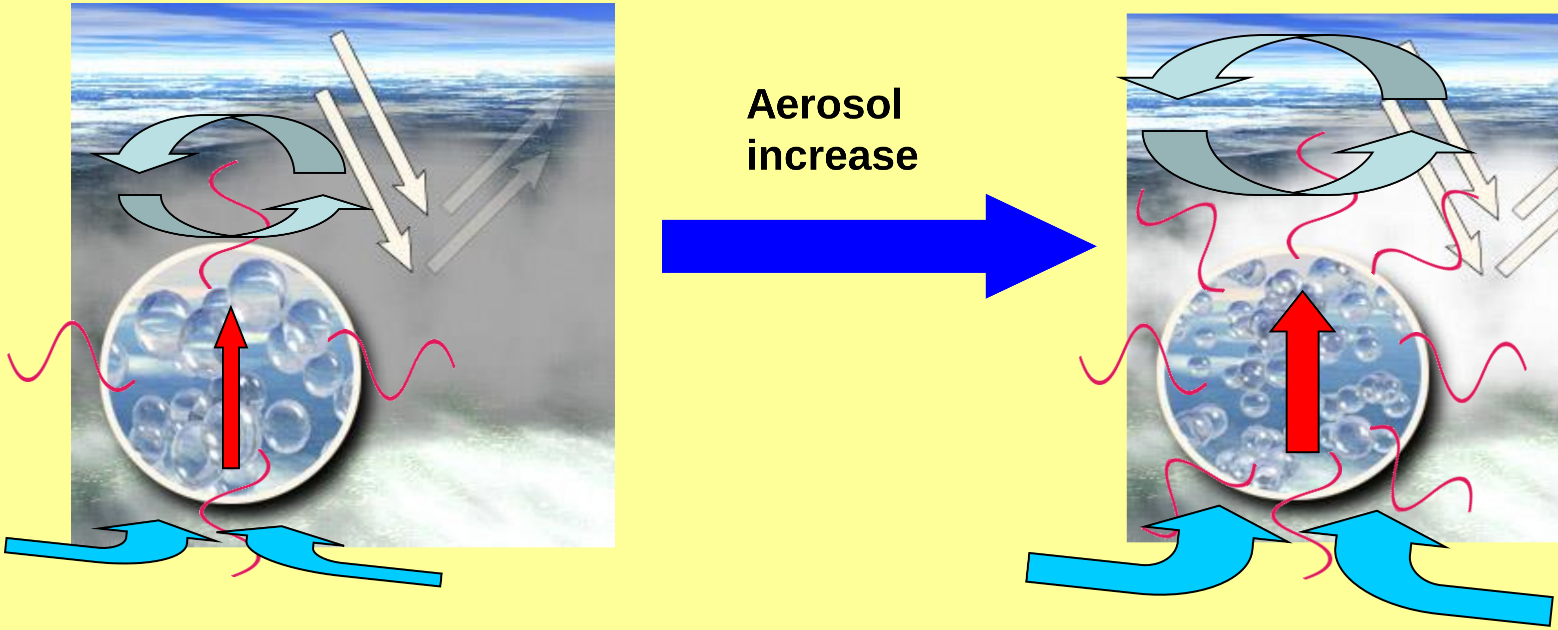


- Decreasing particle size induces

1) More reflection of solar radiation (aerosol first indirect effect)
2) Precipitation suppression (aerosol second indirect effect)

Introduction

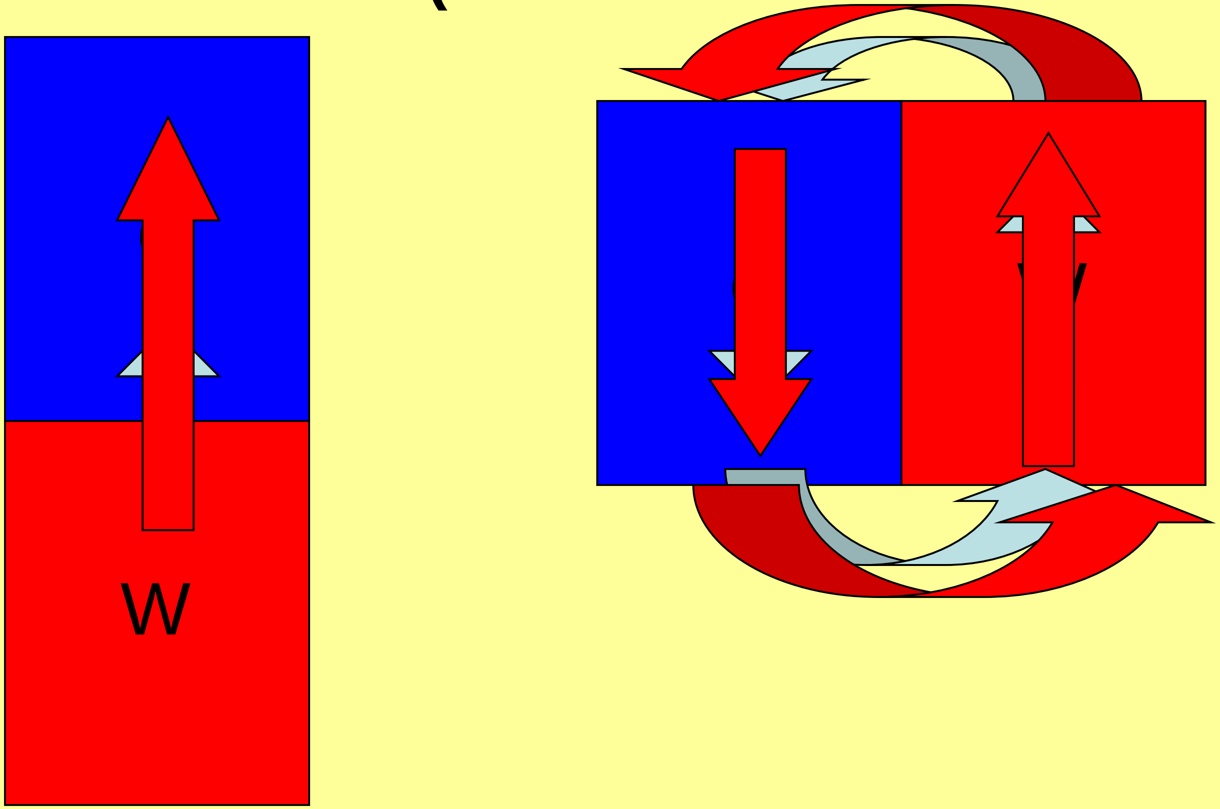
- **Previous studies on aerosol-cloud interactions have focused on the effect of aerosol on microphysical factors only**



Aerosol increase

- **These feedbacks are driven by environment instability**

- Rosenfeld et al. (2008) showed aerosol effects on CAPE (Convective Available Potential Energy) and associated invigoration of convection



CAPE

MAPE
(Mean Available Potential Energy)

Goal

- Explore aerosol-induced changes in the horizontal temperature gradient and associated convective intensity
- Identify mechanisms controlling these changes

Outline

I. The effect of aerosol (as cloud condensation nuclei) on the horizontal temperature gradient and convection

II. The effect of aerosol (as radiation absorbents) on the horizontal temperature gradient and convection

III. Concluding remarks

IV. Ongoing work

I. Aerosol-induced changes in the organization of a tropical system of multiple convective clouds

Introduction

- **The effect of aerosol on deep convective clouds is poorly understood**

- **Aerosol is thought to invigorate deep convective clouds (e.g., Koren et al. 2005; Rosenfeld et al. 2008; Li et al. 2012) but distinct changes in *total* precipitation have not been demonstrated**

- **Aerosol may cause changes in the environment in which convective clouds grow (e.g, Khain et al., 2008; Lee et al., 2011)**

- **Can these changes affect cloud-system organization and the spatial/temporal distribution of rain?**

Goals

- Consider aerosol-cloud interactions for a *cloud system* over days
- Explore mechanisms which control aerosol-induced changes in stability, organization and precipitation in a cloud system comprising multiple clouds

Model Description

- Goddard Cumulus Ensemble (GCE) model coupled with double-moment microphysics (Saleeby and Cotton, 2004)

- Interactive aerosol

Case

- A mesoscale system of deep convective clouds (reaching the tropopause)

- Based on observations during Tropical Warm Pool – International Cloud Experiment (TWP-ICE) Darwin, Australia (Fridlind, 2009)

- Two-day simulations (most convective period)

- Conditions as prescribed by GCSS TWP-ICE case study

Simulations

2-D domain: 185 x 20 km^2
Δx = 500 m and Δz = 200 m

PBL aerosol number concentration:

- **Control run : ~ 400 cm^{-3} (Control)**
- **High-aerosol run: ~ 4000 cm^{-3} (High Aerosol)**

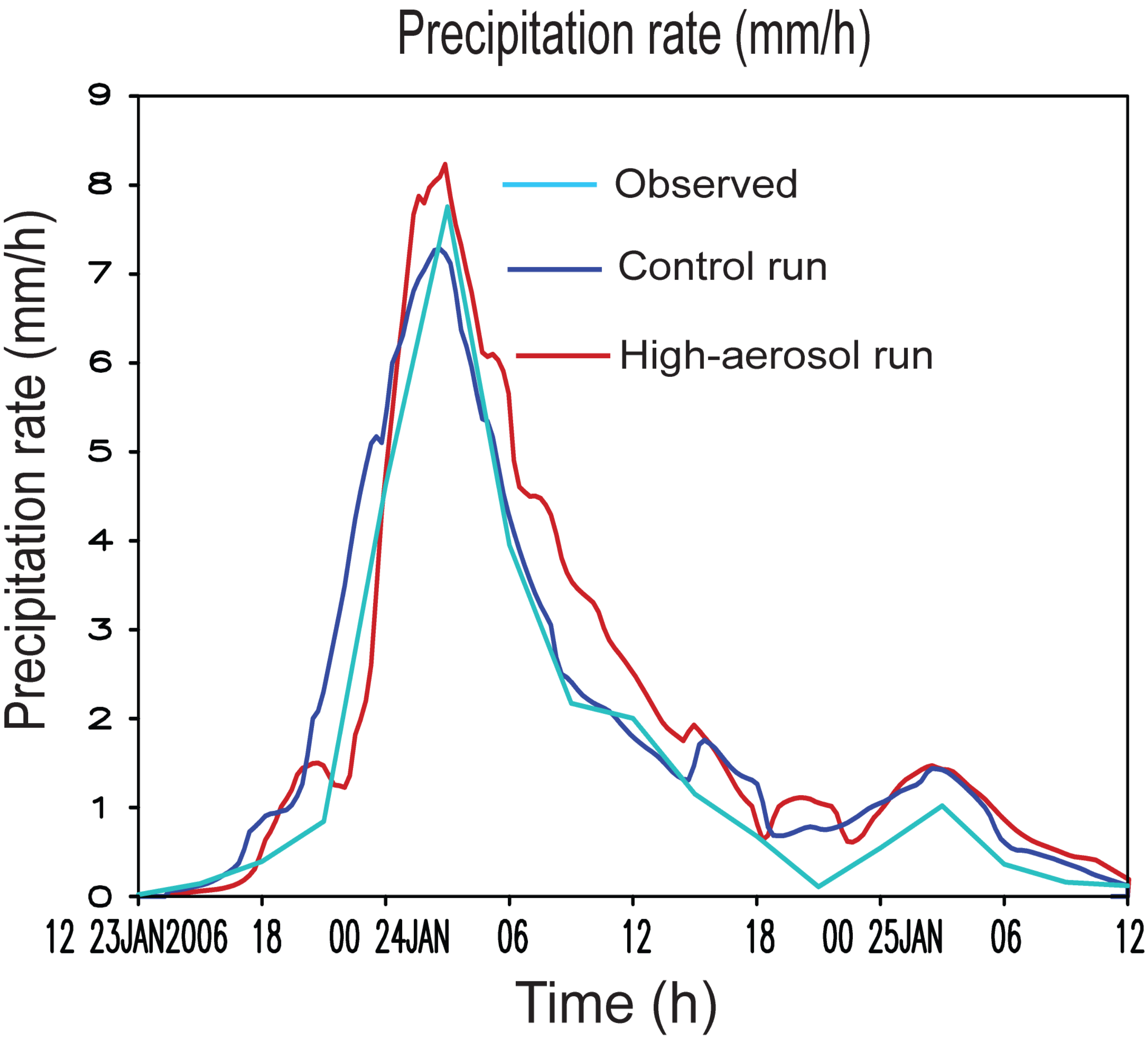
Small Differences in Total Precipitation

Cumulative Precipitation (mm)

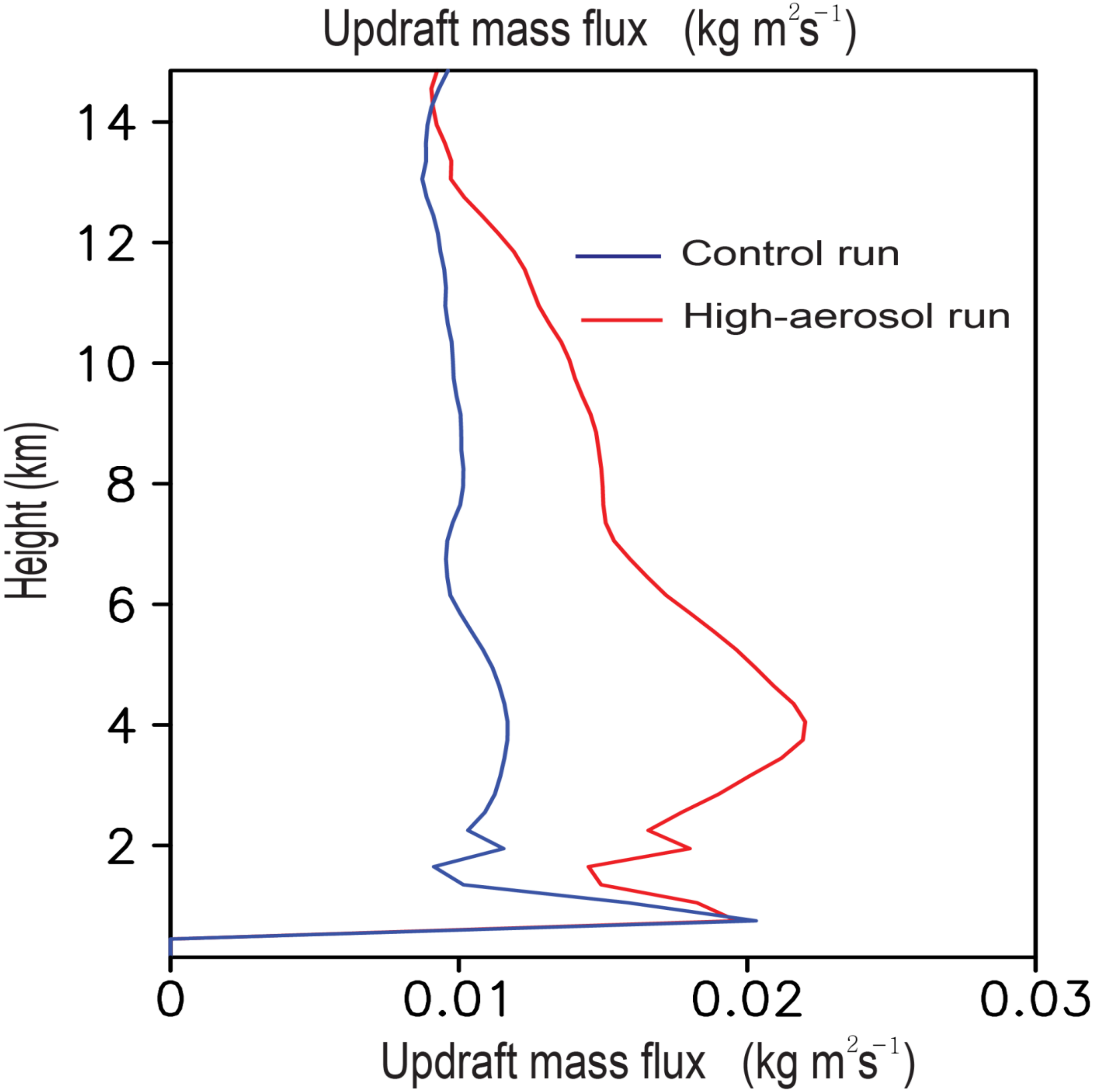
Control: 88.6

High-aerosol: 95.7

(9% increase)



Significant Increase in Updraft Mass Flux



Cloud Response to an Increase in Aerosol

↑ Condensation → ↑Cloud liquid

∝ Accretion of cloud liquid

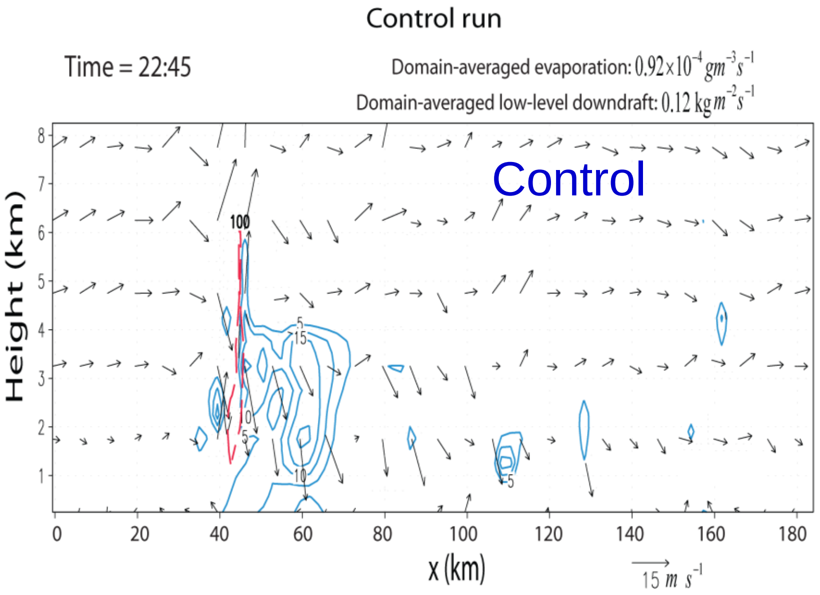
→ ↑Accretion of cloud liquid

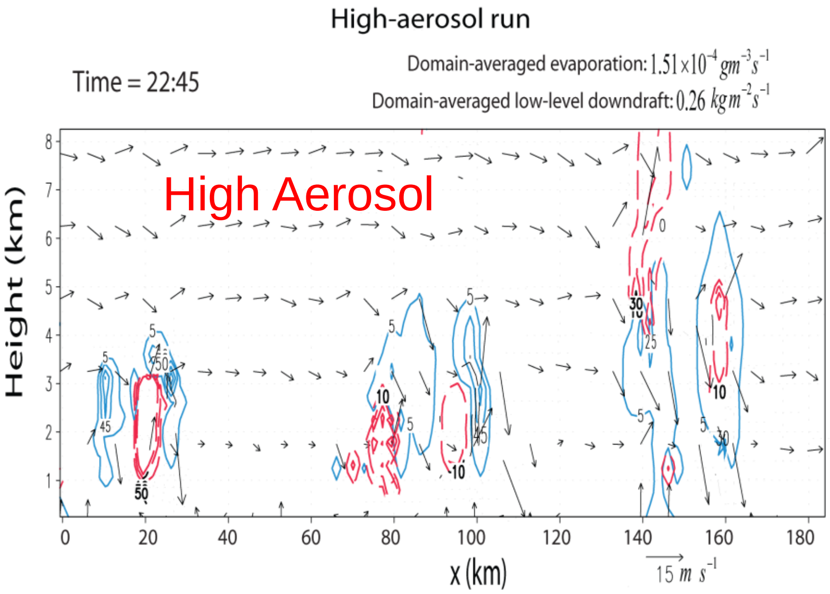
- ➢**Precipitation Budget (High - Control)**

△Precipitation ≈ △ Autoconversion +
2.84 mm -21.08 mm

△Accretion of cloud liquid
23.91 mm

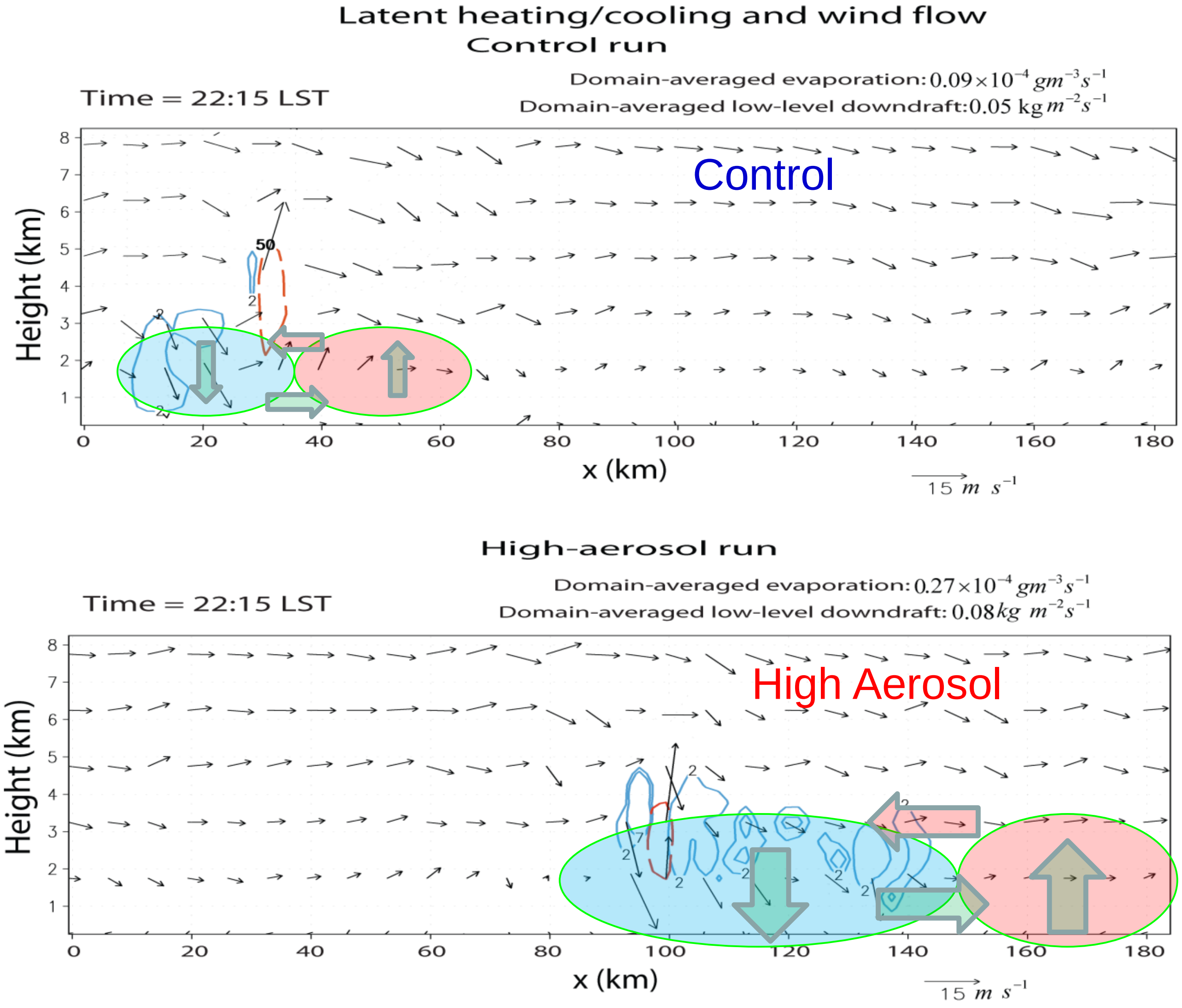
Distinct Differences in Cloud Field Properties





Condensation/evaporation rates and wind flow

Enhanced Evaporation in High Aerosol Run



Latent heating/cooling and wind flow
Control run

Time = 22:15 LST

Domain-averaged evaporation: $0.09 \times 10^{-4}\ gm^{-3}s^{-1}$
Domain-averaged low-level downdraft: $0.05\ \mathrm{kg}\, m^{-2}s^{-1}$

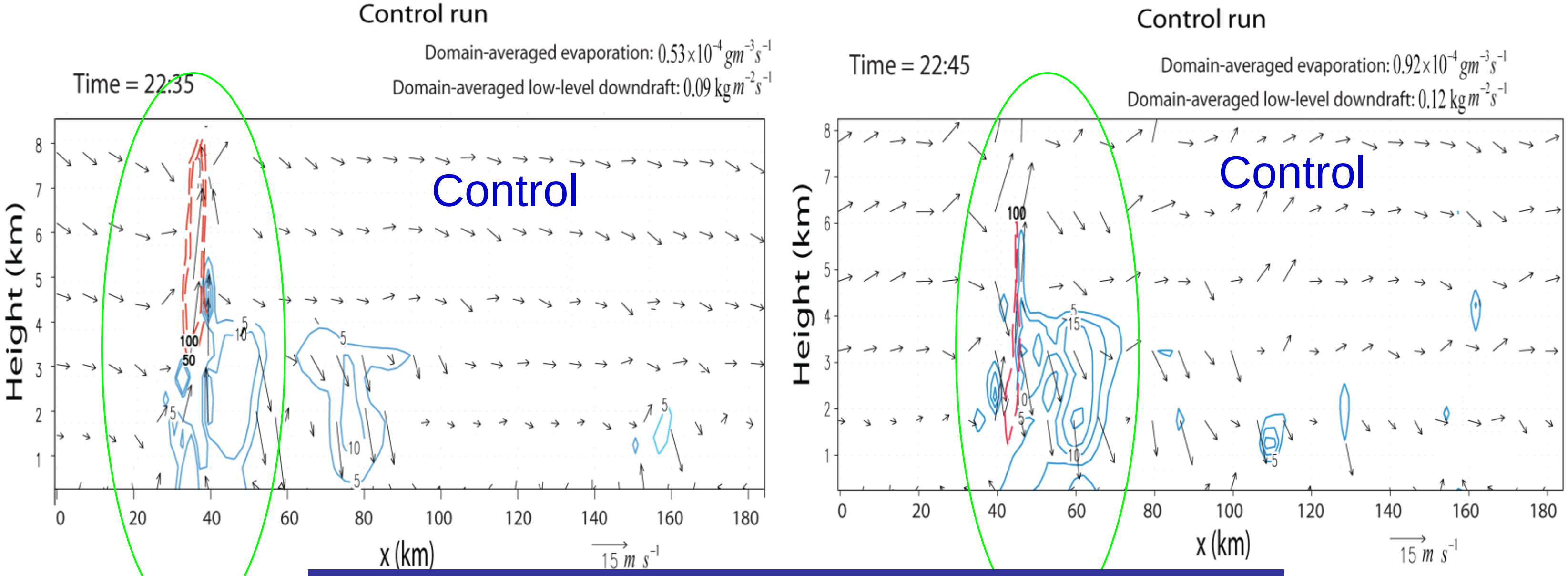
High-aerosol run

Time = 22:15 LST

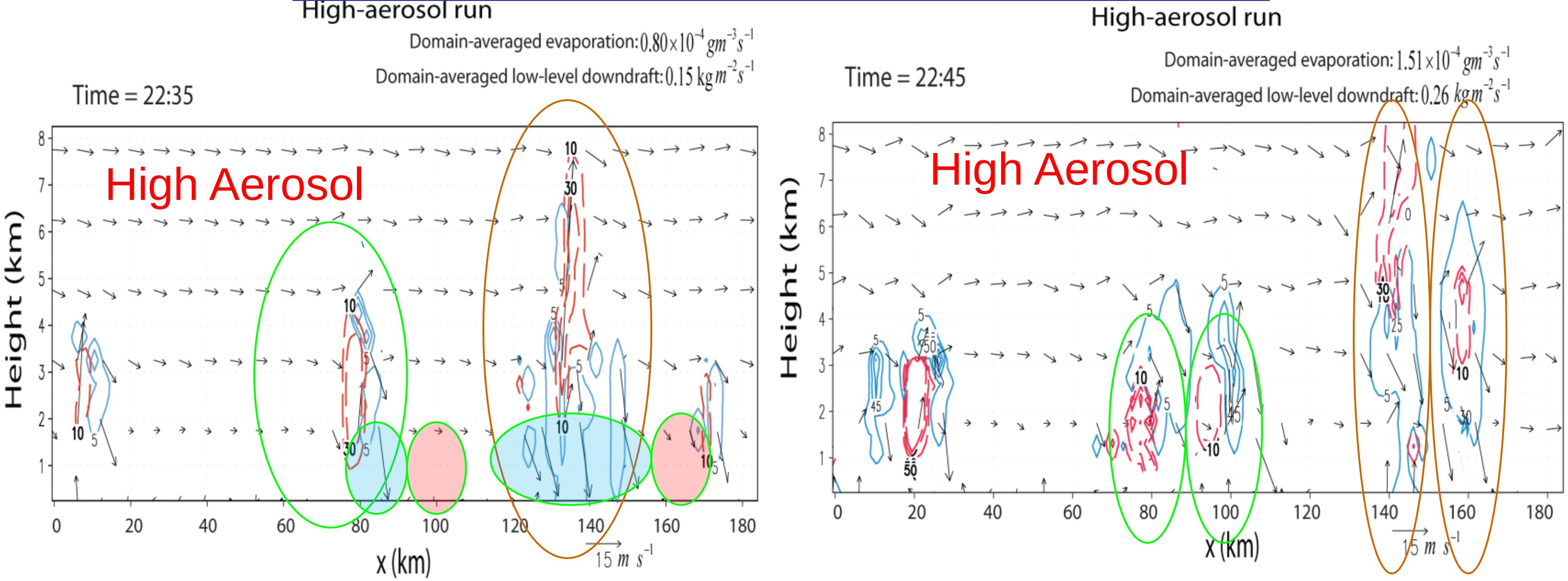
Domain-averaged evaporation: $0.27 \times 10^{-4}\ gm^{-3}s^{-1}$
Domain-averaged low-level downdraft: $0.08\, kg\ m^{-2}s^{-1}$

Condensation/ evaporation rates and wind flow

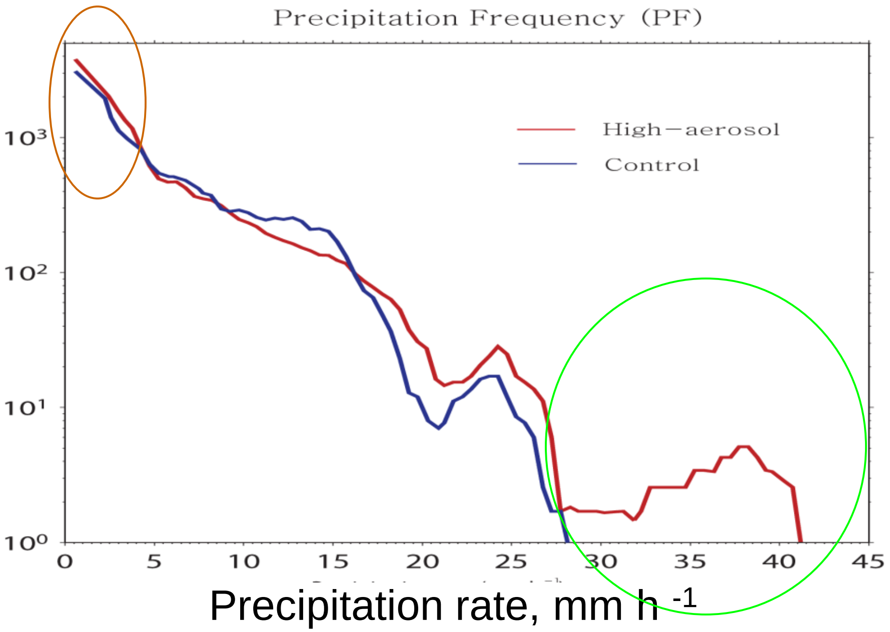
More numerous, smaller cells in High Aerosol Run



Condensation/evaporation rates and wind flow



Precipitation Frequency



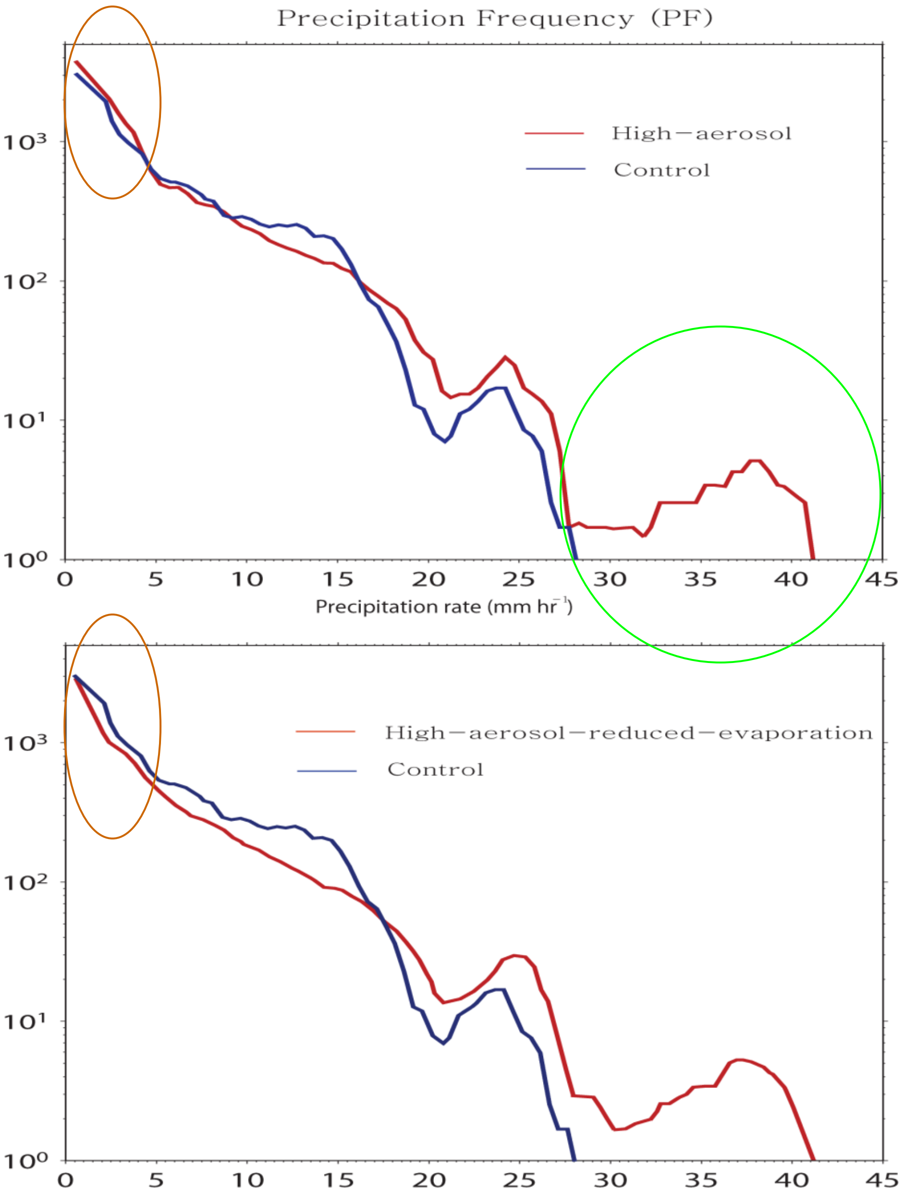
Precipitation rate, mm h^{-1}

Equivalent cloud radius for liquid phase clouds

Cumulative precip (mm) (cloud radius, km)

- Control: 88.6 (7.1 km)
- High-aerosol: 95.7 (5.6 km)

Precipitation Frequency

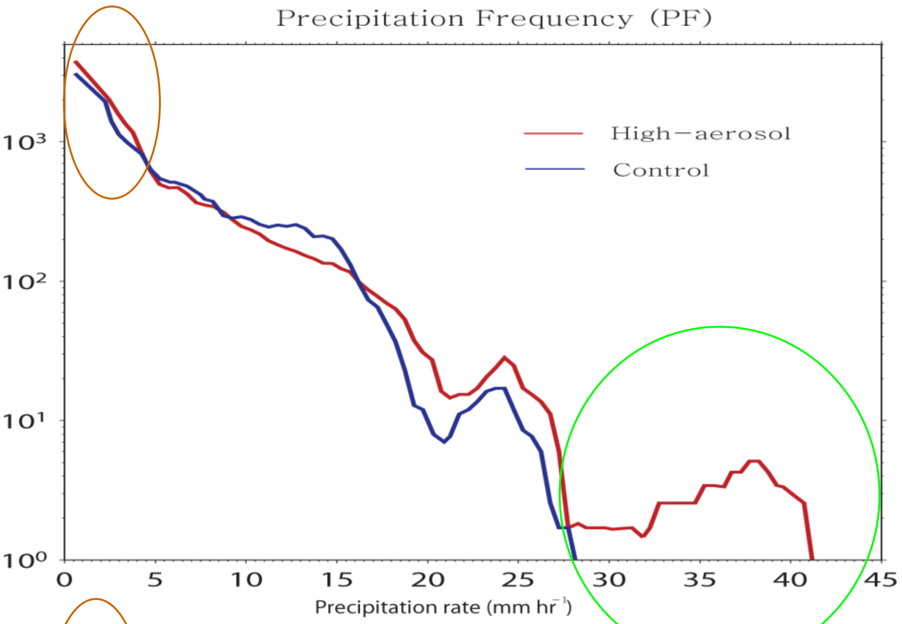


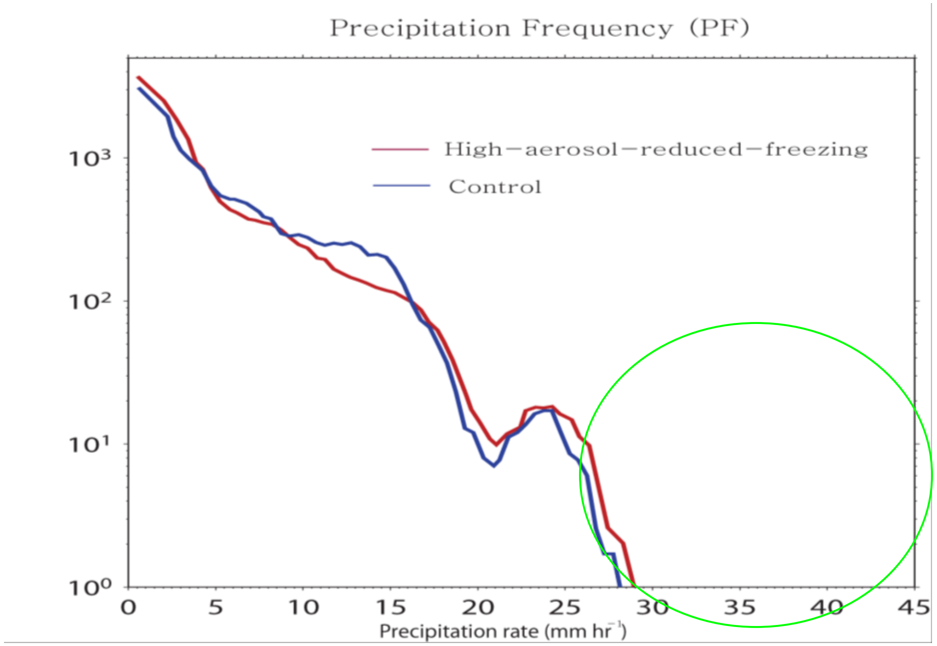
Precipitation rate, mm h $^{-1}$

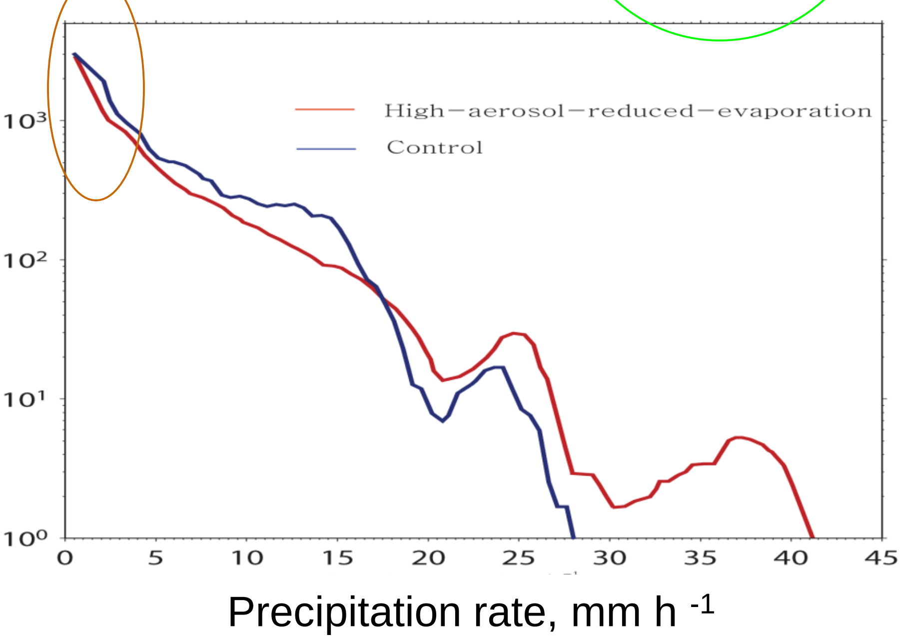
Cumulative precip (mm) (cloud radius, km)

- Control: 88.6 (7.1 km)
- High-aerosol: 95.7 (5.6 km)
- High aerosol-reduced-: 80.7 (7.5 km) evaporation

Precipitation Frequency







Cumulative precip (mm) (cloud radius, km)

- Control: 88.6 (7.1 km)
- High-aerosol: 95.7 (5.6 km)
- High-aerosol-reduced-: 80.7 (7.5 km) evaporation
- High-aerosol-reduced-: 94.2 (5.3 km) freezing

Discussions and Conclusions (I)

- For 2-day TWP-ICE simulations a 10-fold aerosol perturbation has a small effect on total precipitation (+9%)
- More significant changes to cloud system organization and the frequency distribution of rain rates
    - High aerosol simulations have larger number of small clouds (delayed autoconversion, more evaporation, stronger gustiness)
    - Aerosol-enhanced evaporation creates smaller clouds with lower rainrates
    - Aerosol-induced increase in freezing causes intermittent heavy precipitation, however, its impact on cloud-system organization is negligible
- We stress the importance of considering aerosol-precipitation interactions in cloud systems of long duration

II. Aerosol-induced heating of the atmosphere and its effect on warm cumulus clouds

Introduction

- Warm cumulus clouds are linked to climate tightly (Sengupta et al, 1990; Bony and Dufresne, 2005)
- Black carbon aerosol heats and stabilizes the atmosphere (e.g., Hansen et al., 1997)
- Aerosol can induce horizontal heating and temperature gradient, leading to the development of vorticity or circulation (Kim et al., 2006;Bell et al., 2008)

Goal

- Understand mechanisms through which black carbon aerosol affects circulations and convection in warm cumulus clouds

Model Description

- WRF model coupled with double-moment microphysics of Feingold et al. (1998) and interactive aerosol module is used

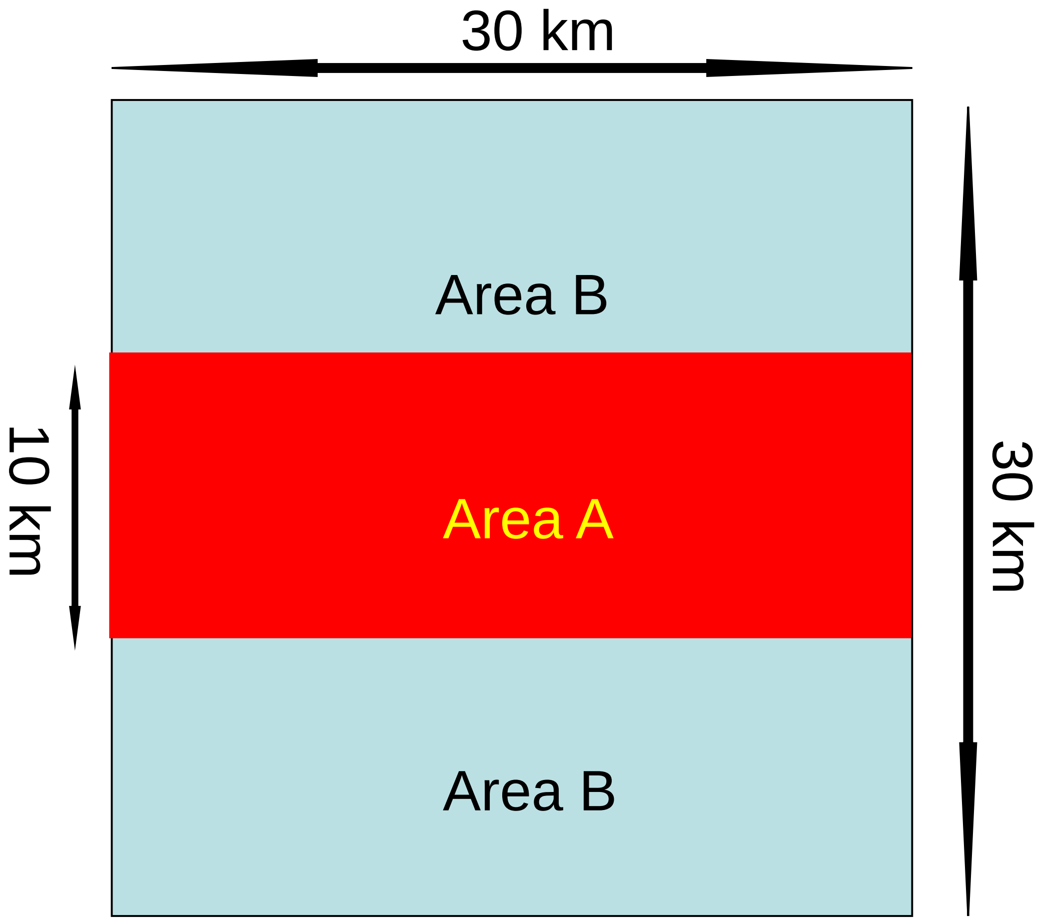
Case

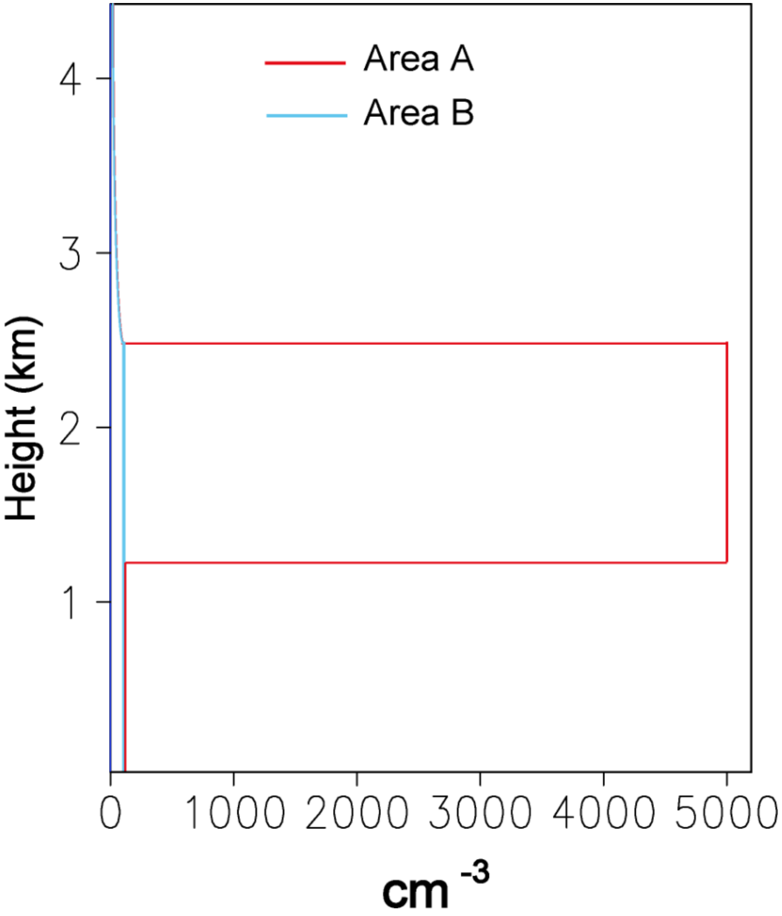
- Smoke Aerosols, Clouds, Rainfall and Climate (SMOCC) case of tropical warm cumulus clouds over the Amazon (Andreae et al., 2004)

Simulations

- 3-D domain: 30 x 30 x 5 km^3
- 9 hour simulations (07 – 16 LST)
- $\Delta x, y = 100$ m and $\Delta z = 50$ m

Horizontal domain and aerosol concentration



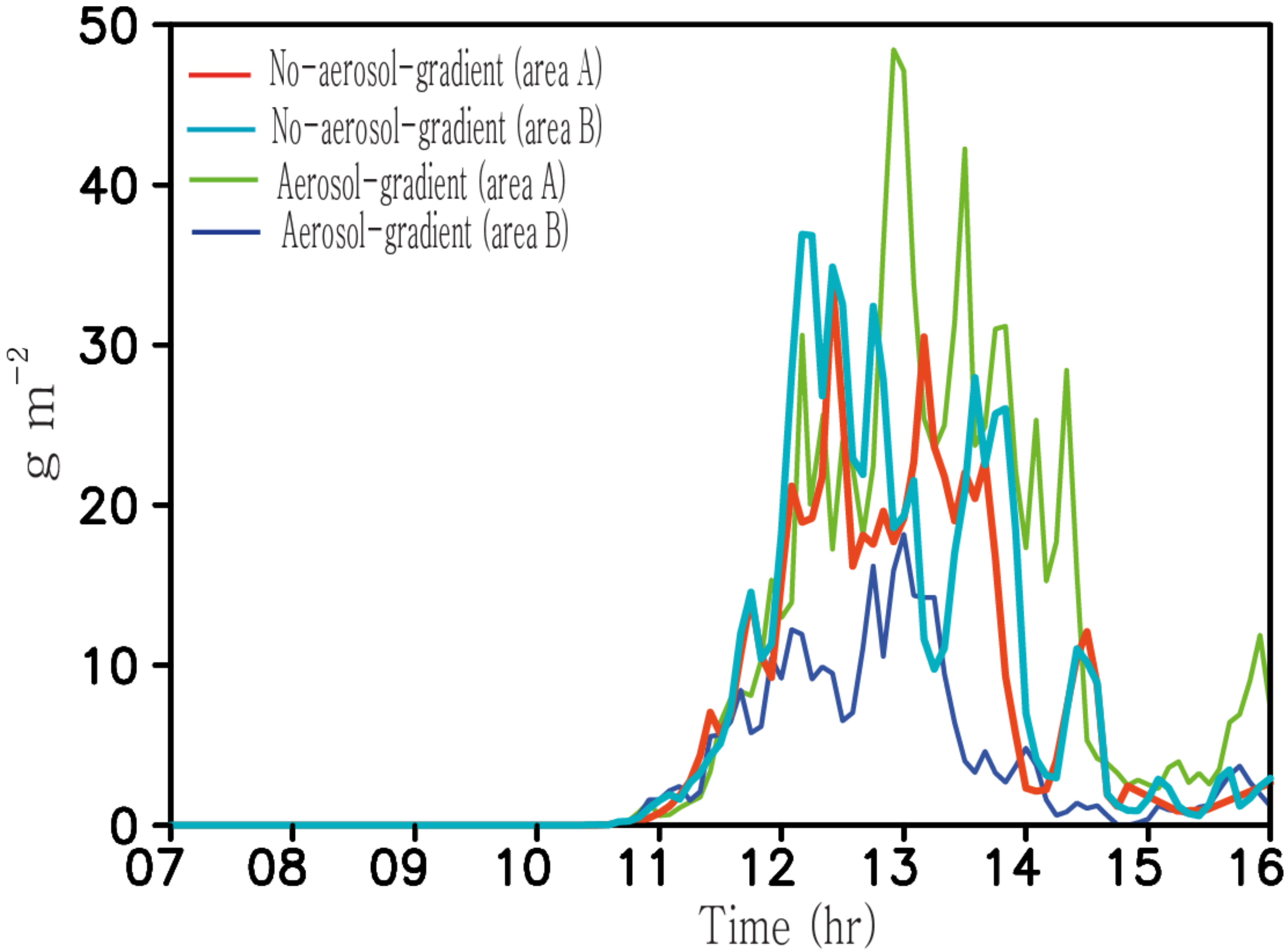


Simulations

1. Aerosol-gradient
(the red line for area A;
the light-blue line for area B)

2. No-aerosol-gradient
(the light-blue line for both areas A and B)

Liquid-water path (LWP) time series



Redistribution of cloud amount by pollution

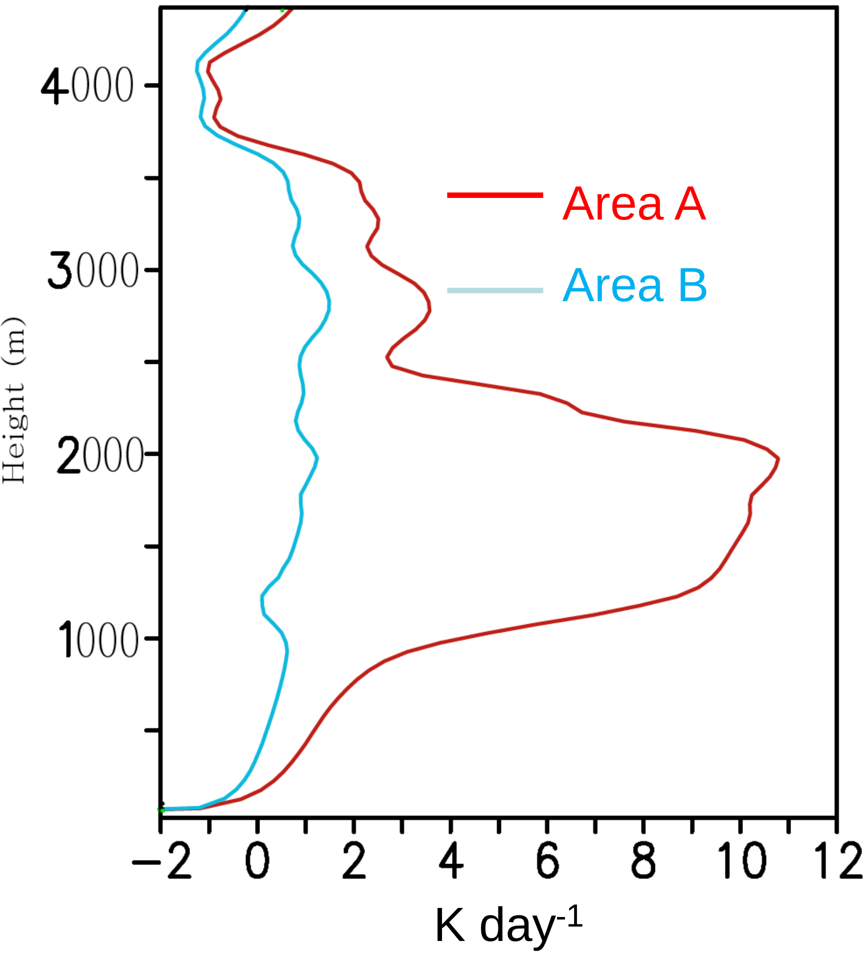
Averaged LWP over the whole domain

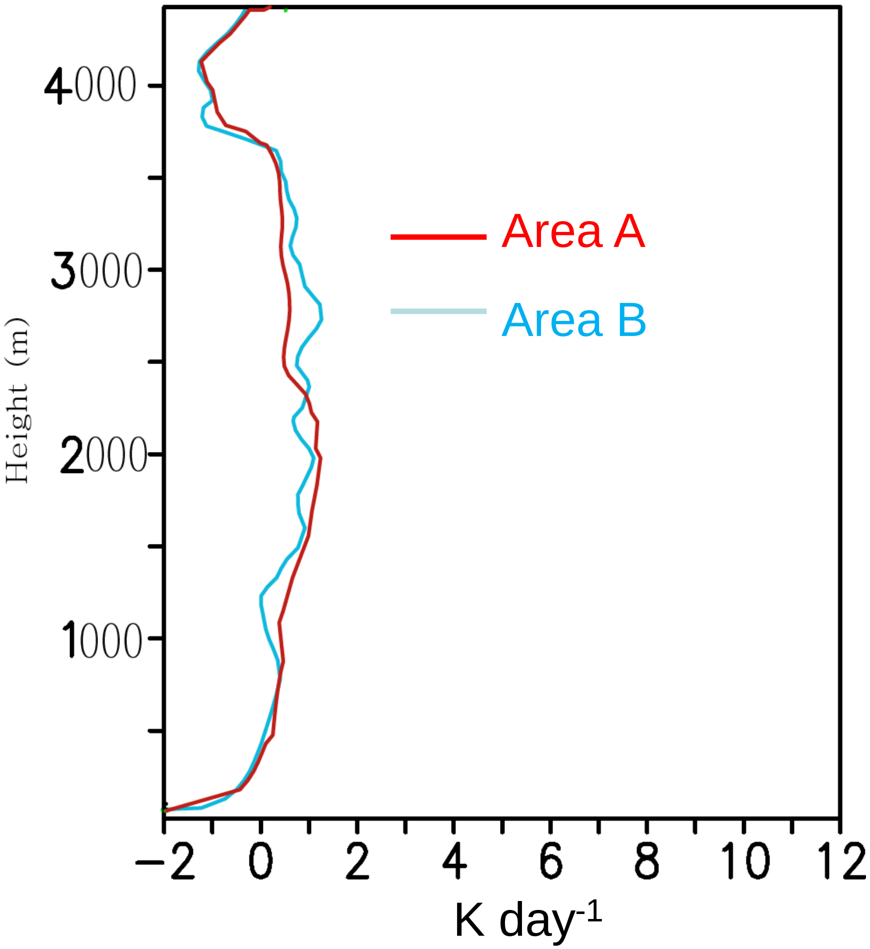
1. **Aerosol-gradient: 7.4 g m^{-2}**
2. **No-aerosol-gradient: 7.6 g m^{-2}**

Radiative heating

Aerosol-gradient

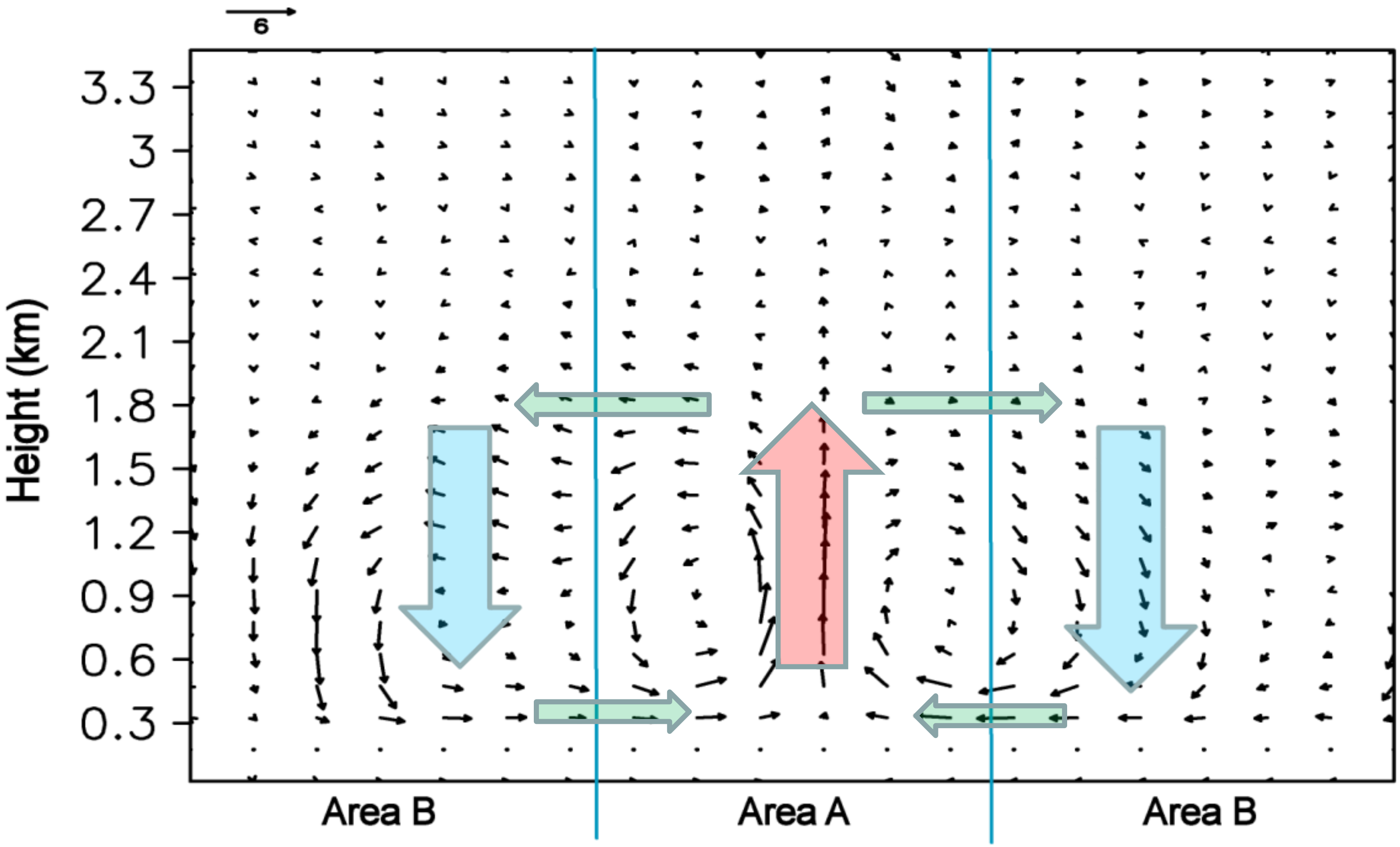
No-aerosol-gradient





Wind vector fields

Aerosol-gradient



Discussions and Conclusions(II)

- The gradient of the aerosol absorption of solar radiation generates the horizontal temperature gradient and circulations
- These circulations affect clouds removed from areas of the source of aerosol pollution (i.e., teleconnection of aerosol effect)
  - This indicates that we need to consider a much larger domain than a domain directly affected by pollution

Discussions and Conclusions

- Aerosol effectively modifies the horizontal temperature gradient in environment
  - Aerosol as CCN intensifies gust fronts in deep convective clouds
  - Aerosol as absorbers generates circulations extending beyond areas directly affected by aerosol pollution
- Understanding of aerosol-cloud interactions should not be limited to in-cloud interactions but extended to interactions between clouds and their environment

Discussions and Conclusions

- Aerosol effects on interactions between clouds and environment do not affect total cloud mass and precipitation amount significantly, but affect their spatiotemporal distribution substantially

- On a global scale and over a sufficiently long period of time, evaporation should balance precipitation at the surface

- Hence, aerosol effects on cloud mass and precipitation should be viewed as their redistribution problem which is closely linked to cloud-system organization

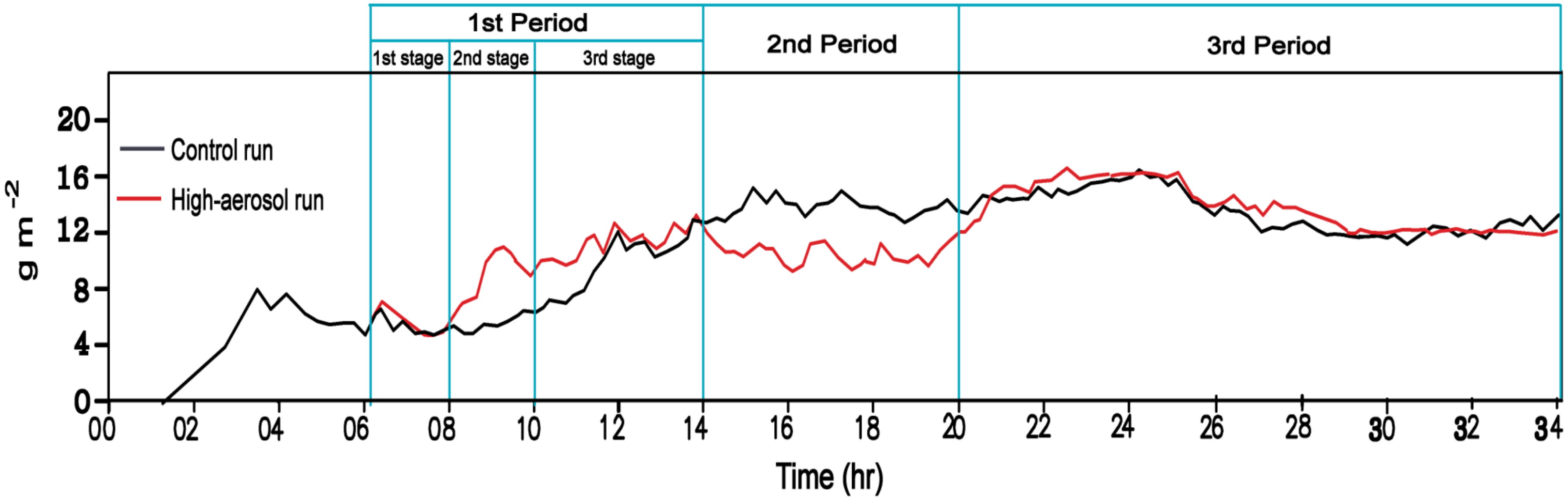
- Cloud-system organization is strongly dependent on the spatiotemporal scale of circulations

Discussions and Conclusions

- Aerosol effects on the redistribution are likely to be different in large-scale circulations such as the Hadley and monsoon circulations

- Aerosol-perturbed systems reach a stable equilibrium state which is similar to unperturbed systems over a long period
of time (Lee et al., 2012; van der Heever et al., 2011)

LWP time series for RICO case (warm cumulus)



Discussions and Conclusions

- For a much longer period and large-scale domain covering the large-scale circulations, what equilibrium in the redistribution and an associated environment will be reached?

Ongoing and future work

Goal

- Perform observational studies on aerosol-induced changes in cloud-system organization and redistributsions

Case I

- **Mixed-phase convective clouds over the Southern Great Plain (SGP) in Oklahoma**

  1. Location

  36.61 °N, 97.49 °W

  2. Period

  23:30 GMT on June 26th
  – 00:00 GMT on July 17th in 1997

Case II

- **Mixed-phase convective clouds over Darwin, Australia (TWP-ICE)**

  1. Location

  12.47 ^{o} N, 130.85 ^{o}W

  2. Period

  00:00 GMT on January 19th
  – 00:00 GMT on February 26th
  in 2006

Instruments

- Cloud-system organization
  GOES-8 and
  MTSAT-1R satellite data

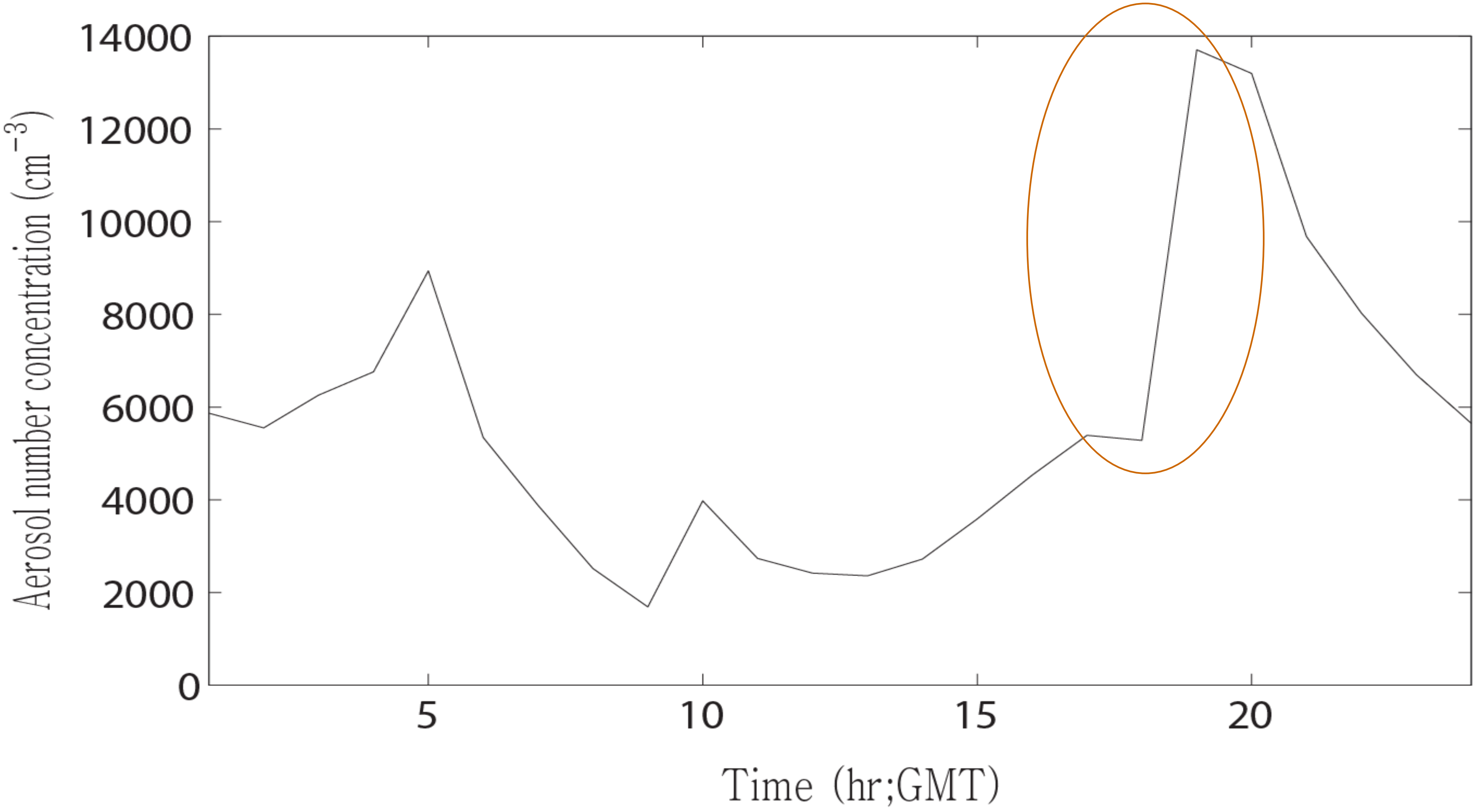
(In collaboration with experts on satellites)

- Precipitation distributions
  C-POL radar data

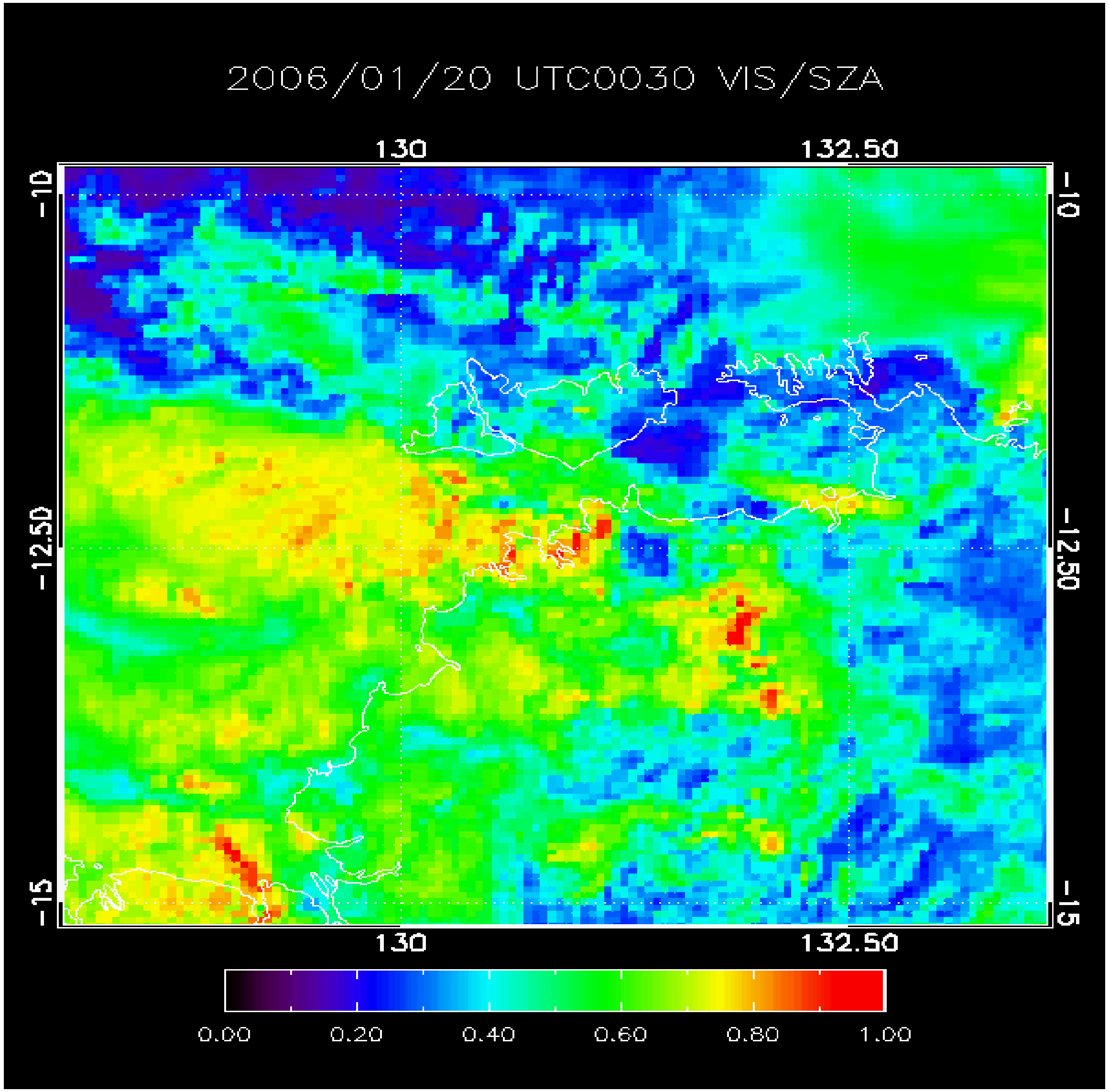
- Aerosol ground observation and satellite

(In collaboration with experts on satellites and ground observation)

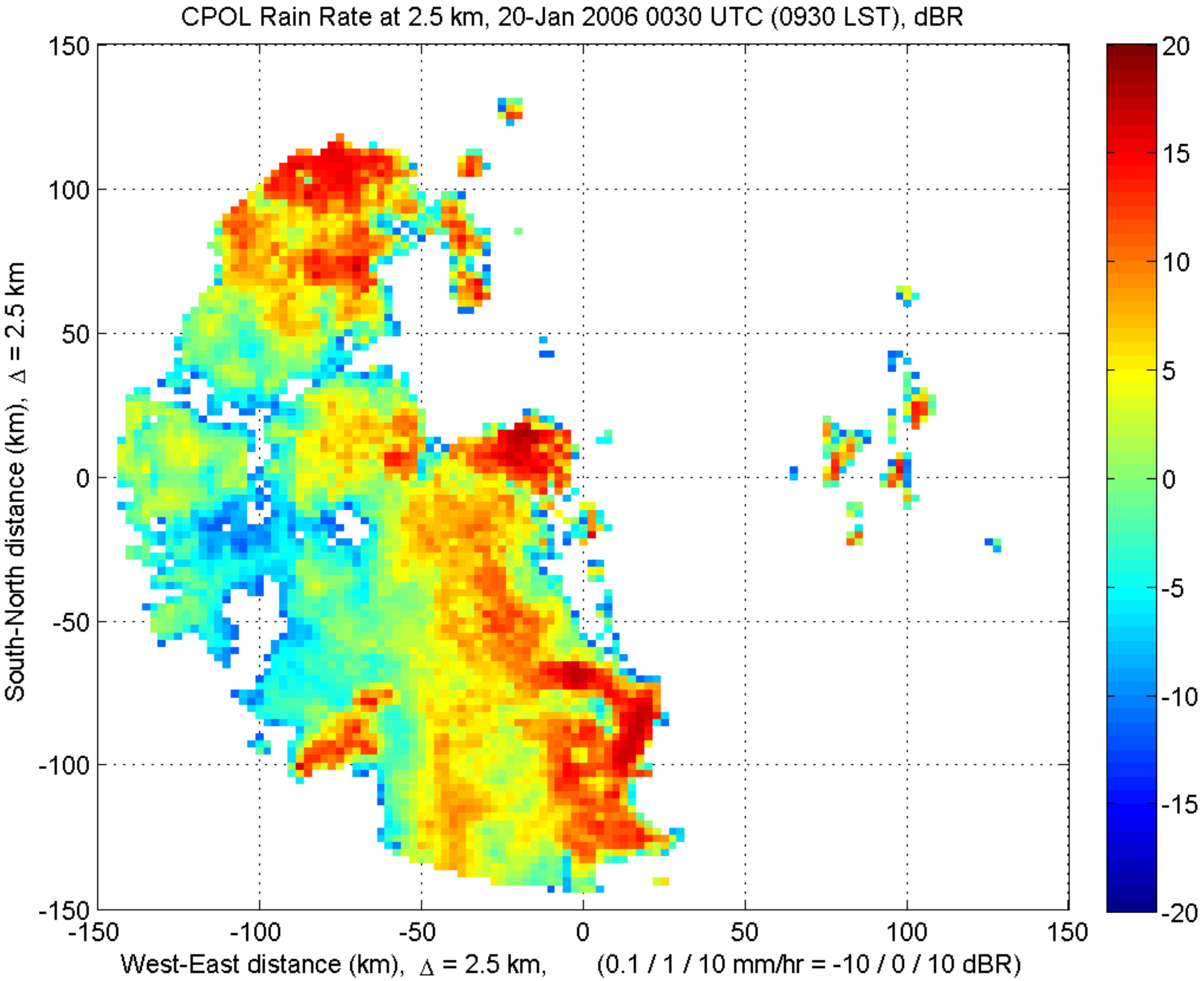
Time series of aerosol number concentration on June 27 1997 for the SGP case



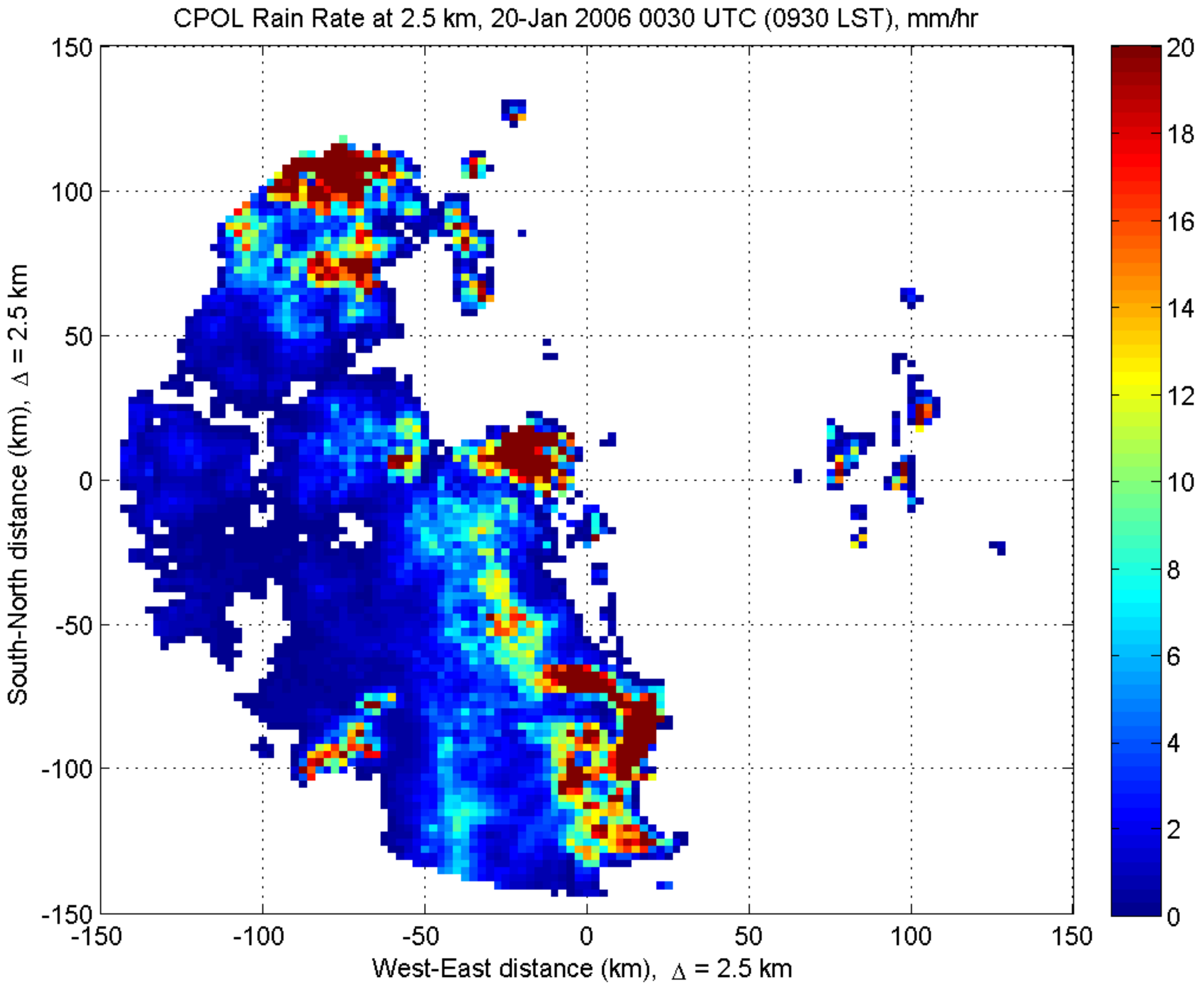
Satellite reflectivity for TWP-ICE



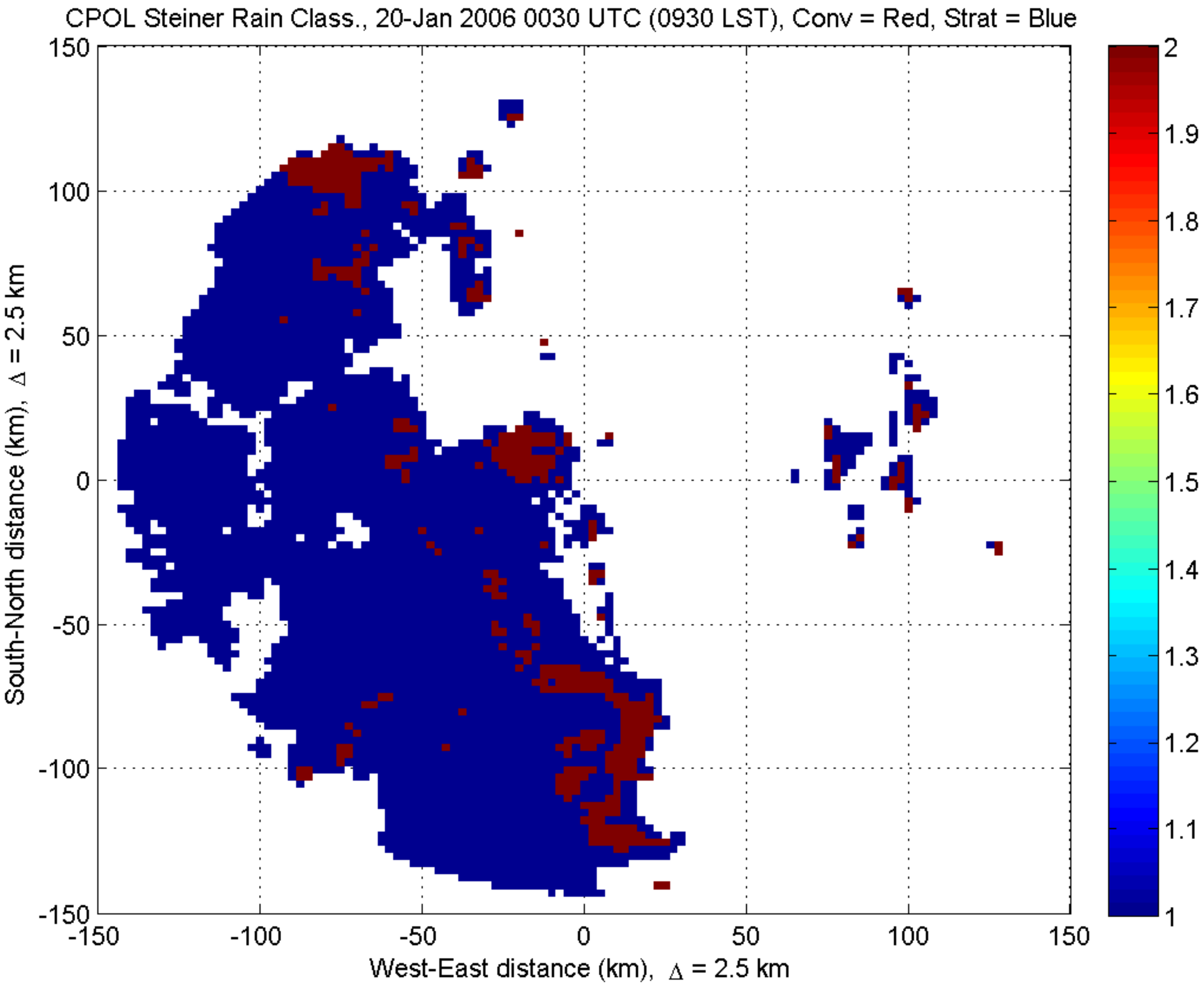
Radar reflectivity for TWP-ICE



Rain rate for TWP-ICE



Precipitation types for TWP-ICE



Future plan

- Separate aerosol effects from meteorological influences

(In collaboration with experts on statistical analysis)

- Compare the observed correlations to those simulated and evaluate simulations

(In collaboration with experts on regional modeling)

- To make results more robust, repeat these processes for more selected periods

- Extend this study to mixed-phase clouds and other types of clouds such as ice clouds, cumulus and stratocumulus clouds in other regions

Funded projects

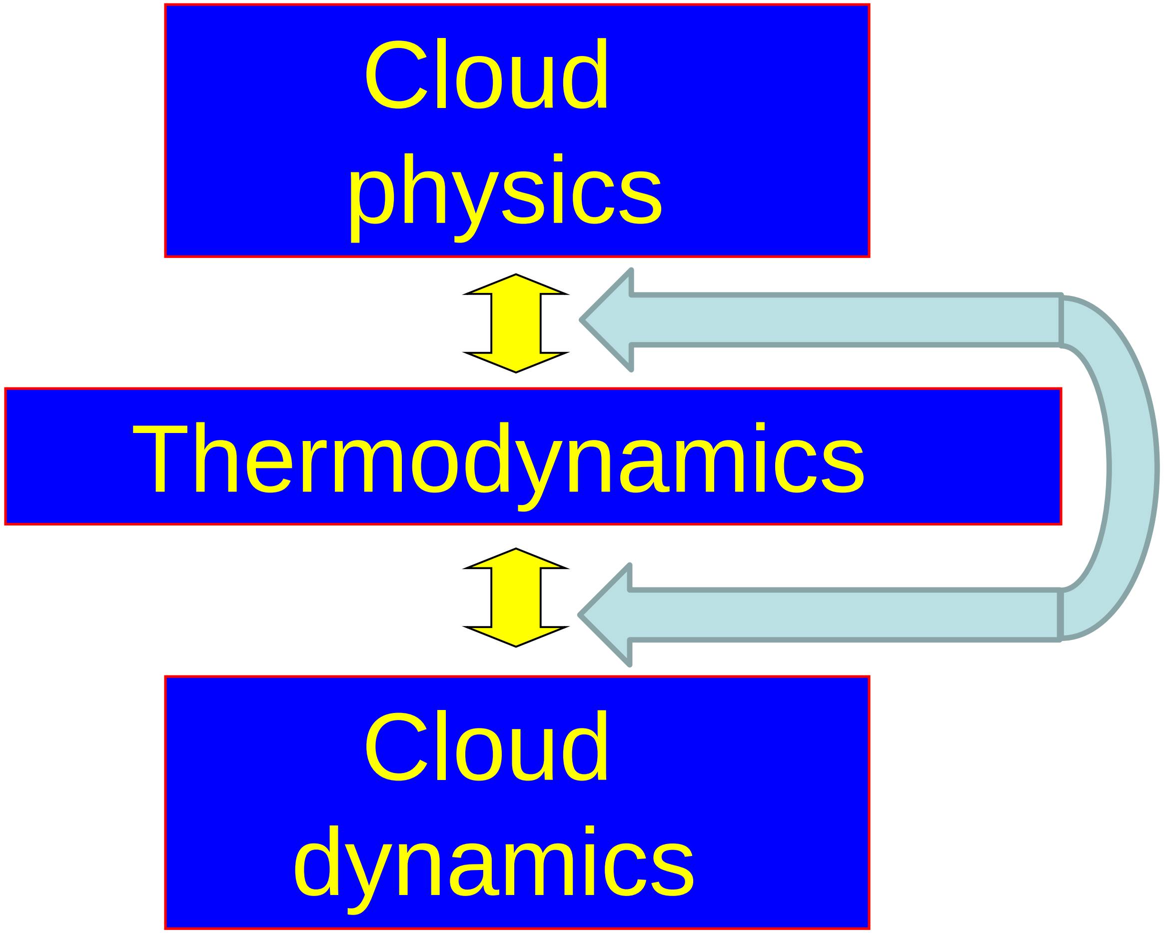
- **Interactions between tropical biomass burning, clouds, precipitation and land use on over the Amazon**

- **Interactions between urban pollution, mesoscale convective systems, torrential rain and land use over Seoul**

- **Satellite and lidar observation on land use and aerosol**
- **Radar observation on clouds and precipitation**
- **Ground observation on surface fluxes (land use)**
- **LES simulations**
- **Parameterization**

Teaching plan

Introductory courses



Cloud physics

Thermodynamics

Cloud dynamics

Visualization
of
this linkage

Teaching plan

Advanced courses

Cloud physics
- Ice processes

Cloud dynamics
- Cloud system
- Self-organization

Aerosol-cloud-weather interactions
- Fundamental theories

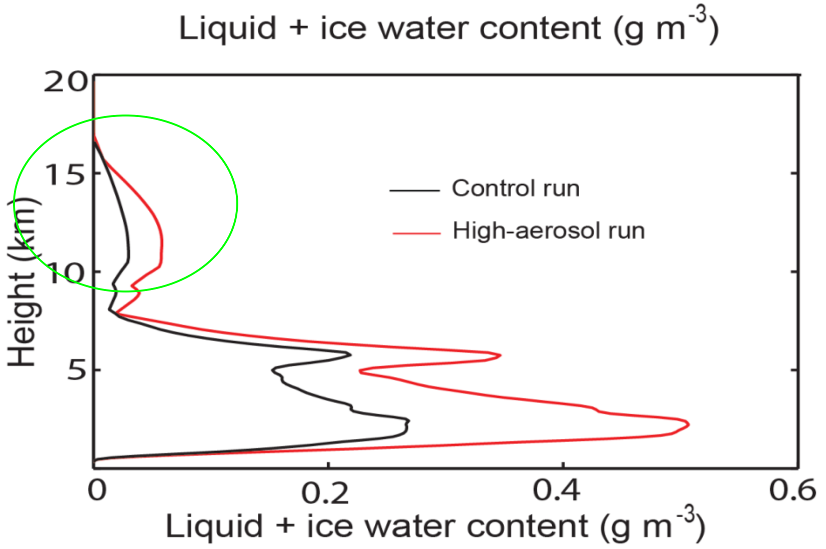
Cloud modeling
- Representations of cloud processes in models

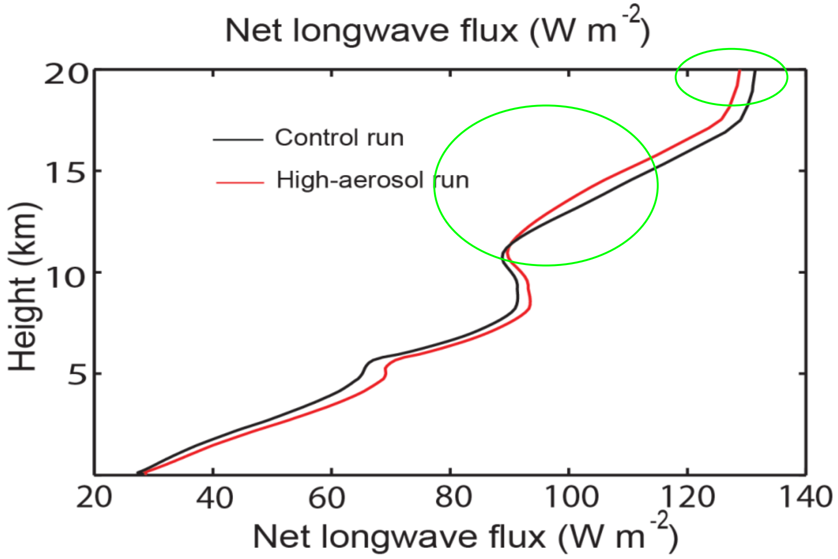
Thanks!

Substantial Offset of Aerosol-Induced Change in Solar Radiative Fluxes by That in Longwave Fluxes

Solar (longwave) radiative fluxes at the top (W m^{-2})

Control run: -118.5 (133.2)
High-aerosol run: -109.2 (129.5)


Liquid + ice water content (g m^{-3})


Net longwave flux (W m^{-2})

Future plan

- Aerosol-cloud interactions are sub-grid cloud-scale interactions from the perspective of climate model

- Parameterizations for aerosol-cloud interactions in climate models have not been able to simulate aerosol-cloud interactions and their impacts on redistributions adequately well

- Aerosol-cloud interactions depend strongly on environmental conditions

- Hence, these interactions vary widely with varying environmental conditions

- It is frustratingly difficult to establish climatically meaningful relationships among the aerosol, clouds and precipitation

- This means that constructing general parameterizations for aerosol-cloud interactions in climate models will be very challenging

- **A large portion of uncertainties of global aerosol-cloud interactions comes from the Northeast Asia (Korea).**
  - Insufficient measurement of aerosol and clouds
  - One of the most important sources of aerosol
  - Asian Monsoon sits on pollution regions
- **Strong shear and low CAPE in Asia (Hong, 2004; Riemann-Campe, 2009);different aerosol-cloud interactions**

- **Utilize ARM mobile facility (AMF) and satellite data**

1. Perform mesoscale simulations (M. Sc. Students)
2. Identify mechanisms of aerosol-cloud interactions in Asia (M. Sc. and Ph. D students)
3. Evaluate these mechanisms using observed data (Ph. D. students)
4. Compare these mechanisms to those in other AMF sites (Ph. D students and postdocs)
5. Establish more generalized parameterizations for aerosol-cloud interactions (Ph. D students and postdocs)

- **Utilize the comparison betweeen a CSRM and a Climate model**

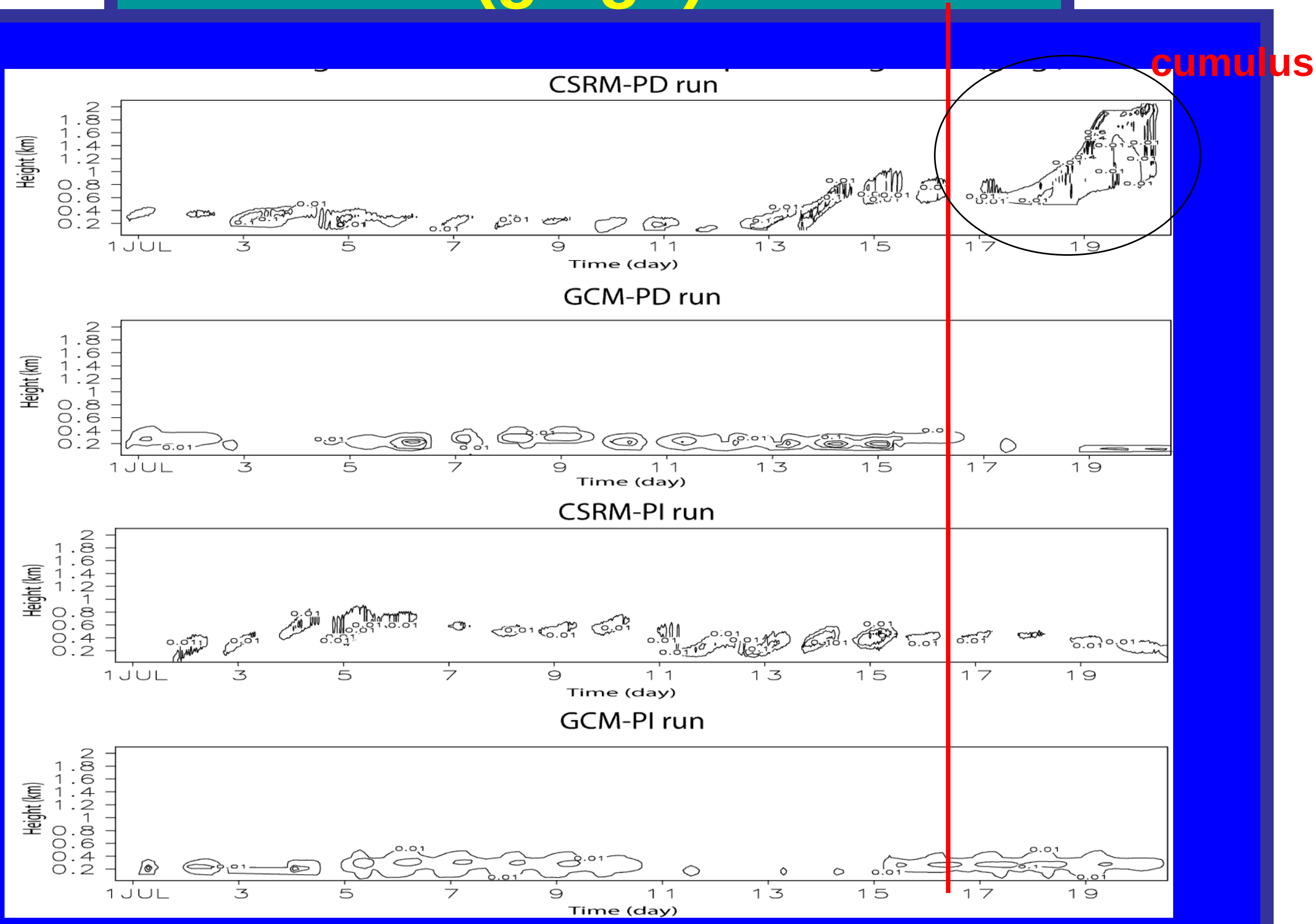
- Extend comparisons to convective, mixed-phase and ice clouds (Ph. D. students and postdocs)

Stratocumulus
(off the coast of the Western Mexico)

	CSRM Preidustrial aerosol (PI)	CSRM Present-day aerosol (PD)
Average LWP (g m^{-2})	7	10
Average shortwave cloud forcing (W m^{-2})	-18	-37

	GCM-PI	GCM-PD
Average LWP (g m^{-2})	16	24
Average shortwave cloud forcing (W m^{-2})	-103	-137

Time-height cross section of cloud-liquid mixing ratio (g kg^{-1})



CSRM-PD run

GCM-PD run

CSRM-PI run

GCM-PI run