Feedbacks Between Cloud Microphysics and Dynamics in Deep Convective Systems

Susan C. van den Heever

with contributions from Stephen M. Saleeby, Robert B. Seigel, Amanda M. Sheffield and Rachel L. Storer

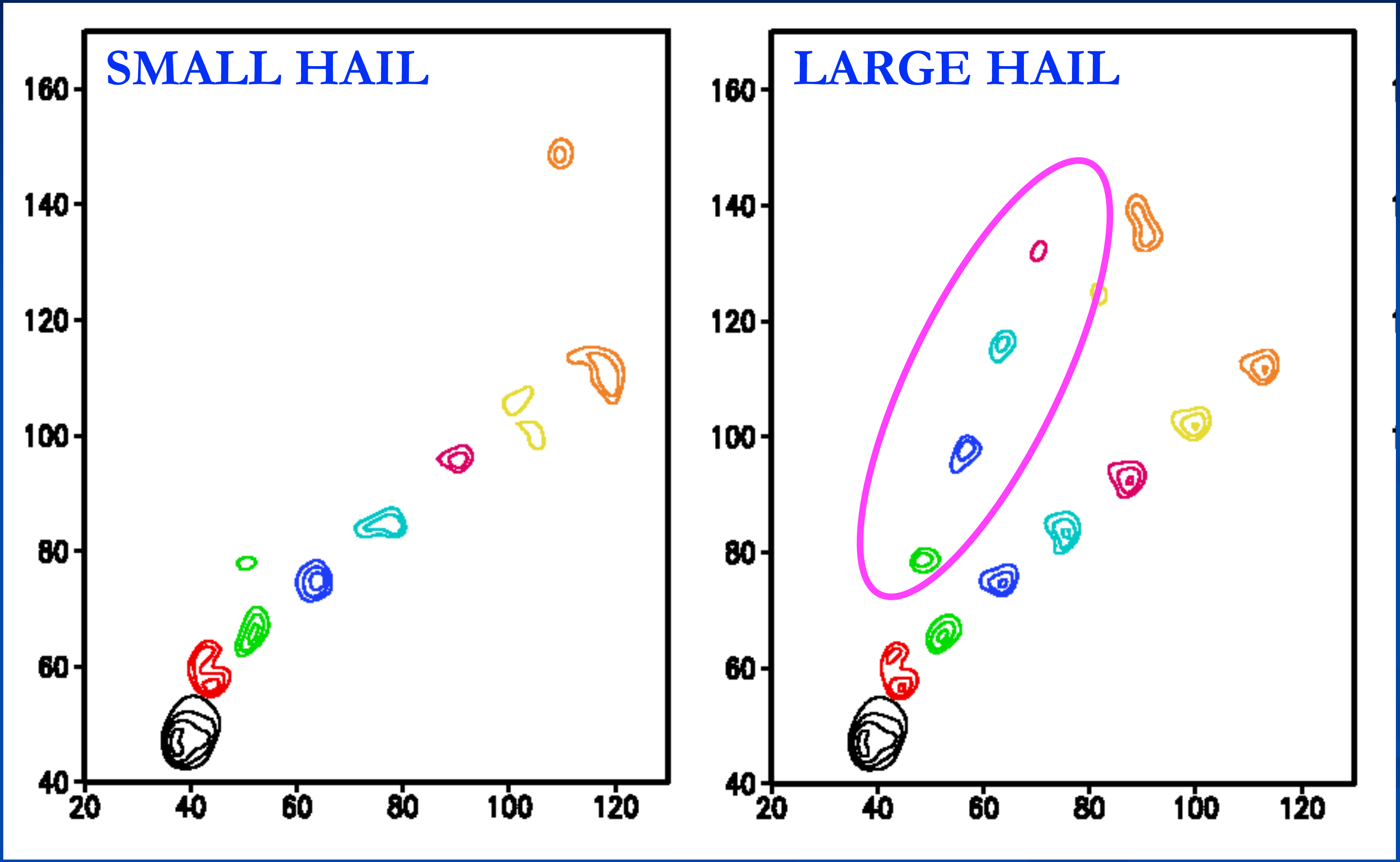
Colorado State University

Fort Collins, CO

Source: University of Arizona


Introduction

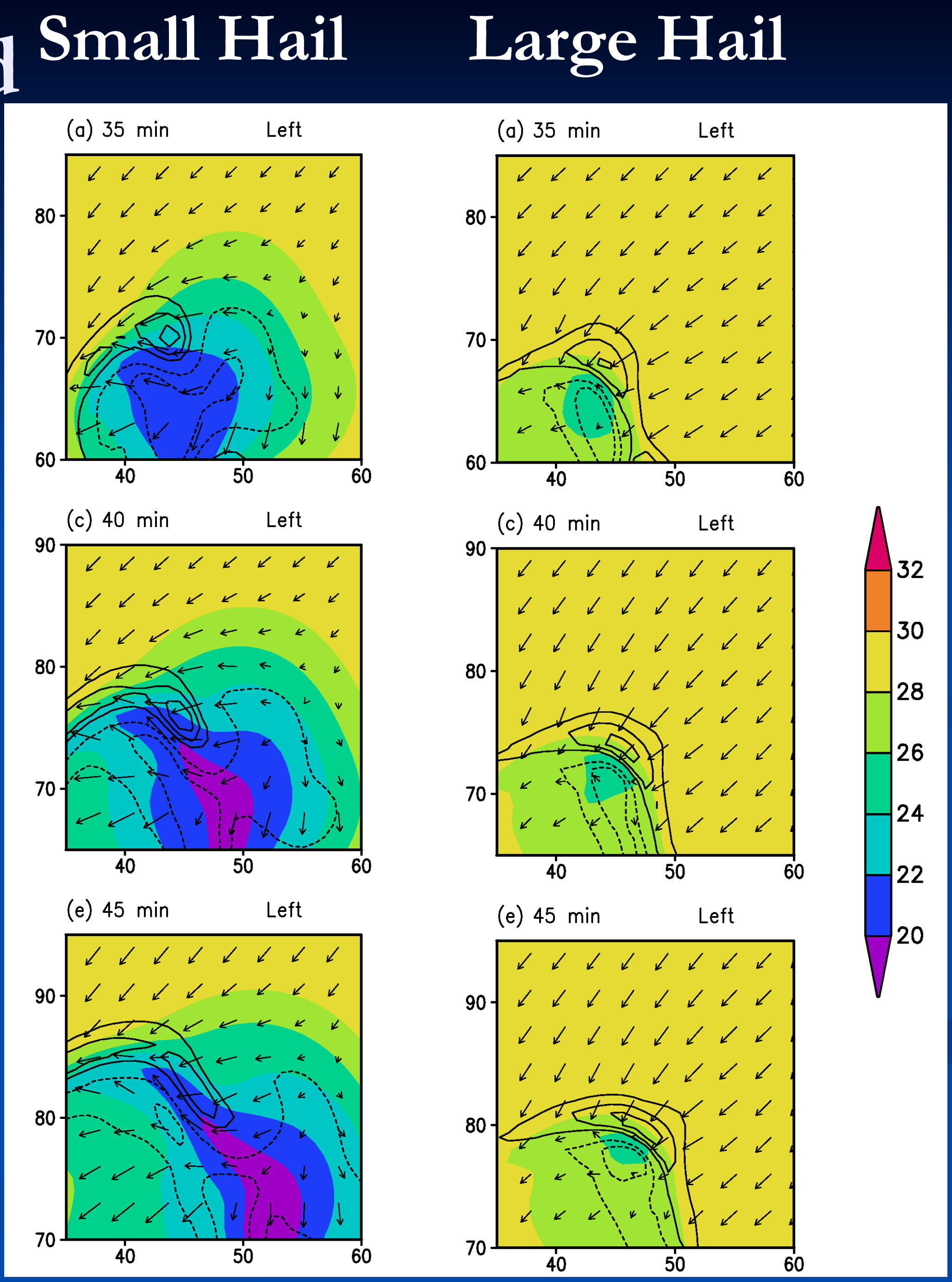
Storm Tracks



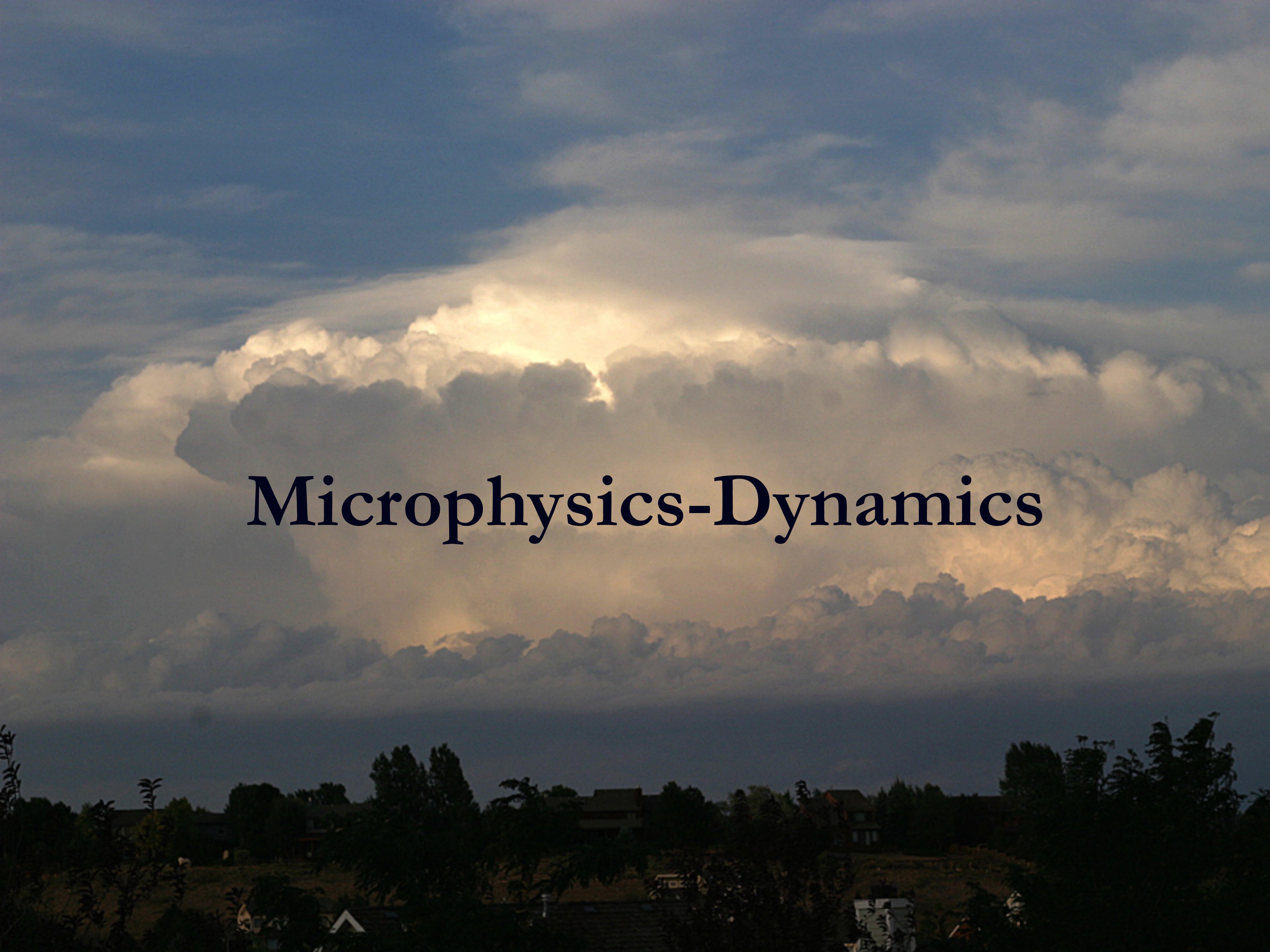
Vertical velocity at 4830m AGL at 15 minute intervals(from southwest to northeast). Contour interval is 10 m/s. Axes are distance (km) from southwest corner of grid.

Storm-Relative Wind Flow

- Small hail: LM air comes predominantly from cold pool
- Large hail: LM air comes predominantly from environment



Temperature (color, °C) and storm-relative wind vectors at 250m AGL


Microphysics-Dynamics

Convective Storm Processes

Storm Dynamics
=> vertical motion

Mixed-Phase / Ice
Microphysics

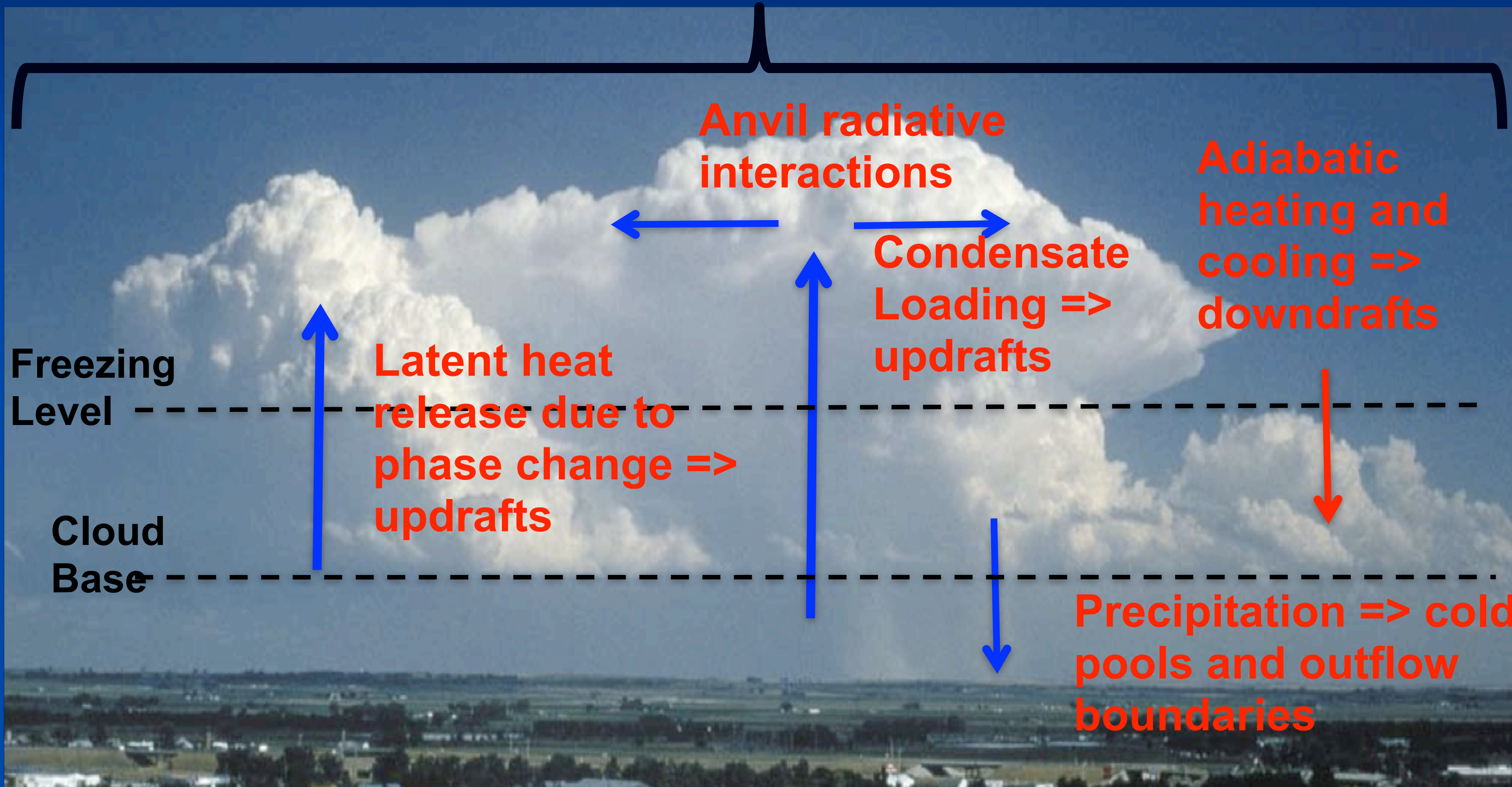
Feedbacks / Links
between them

Coloradoan Dec. 8, 2005

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

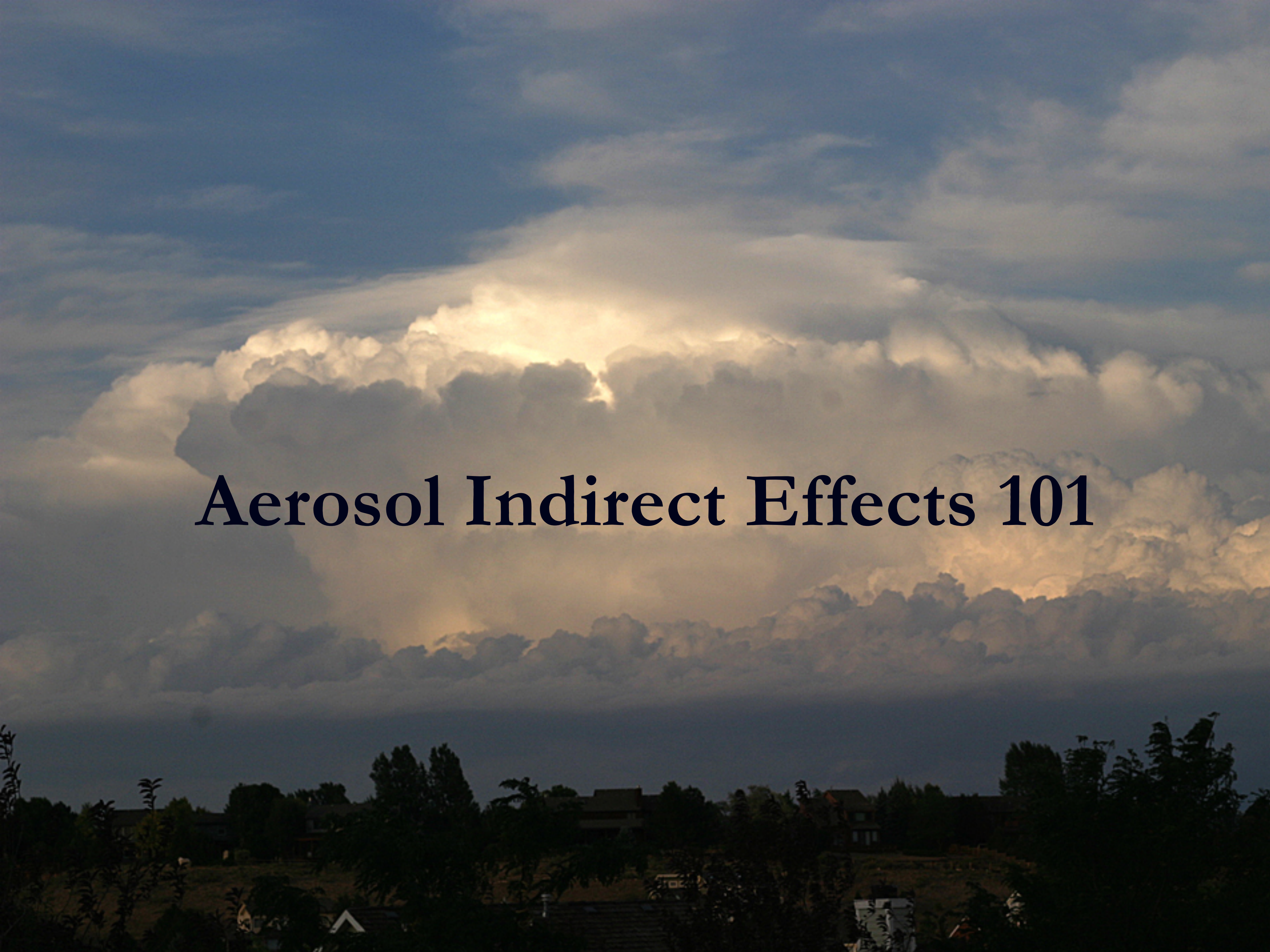
Microphysics ⟷ Storm Dynamics

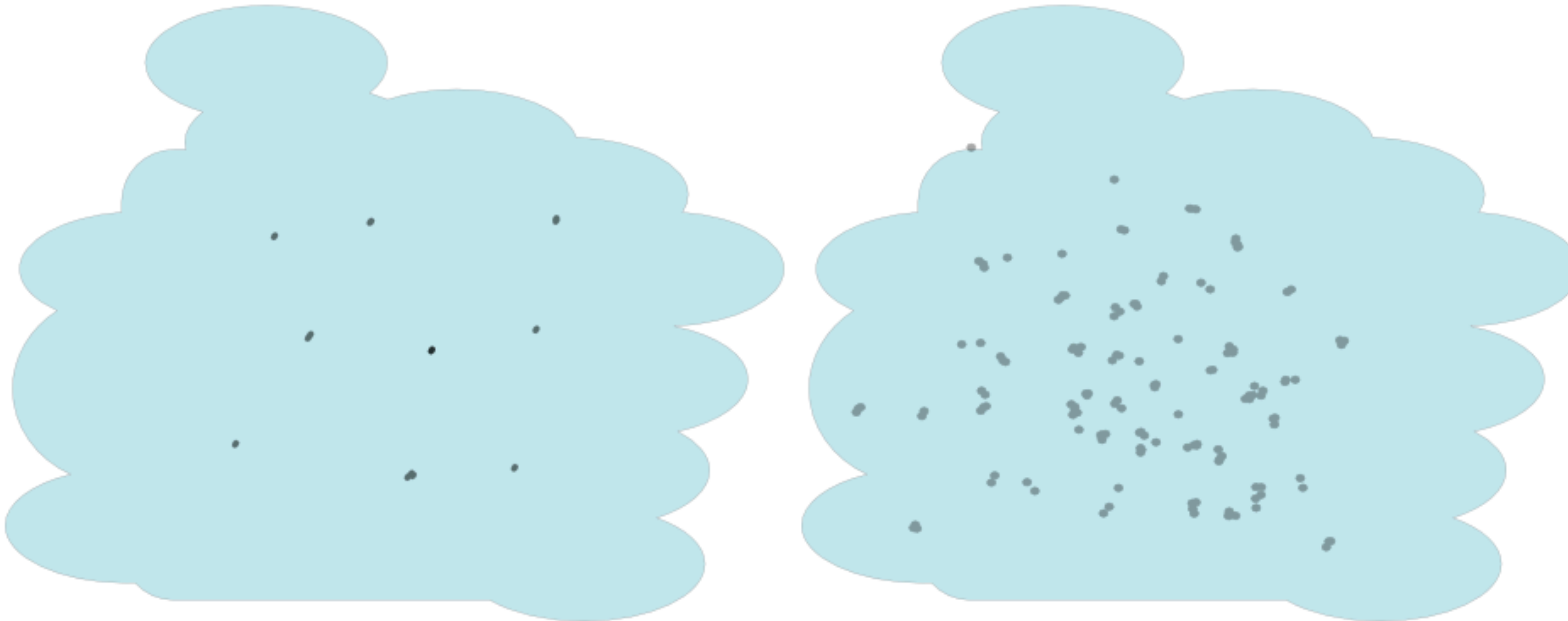
?



Factors Impacting Interactions

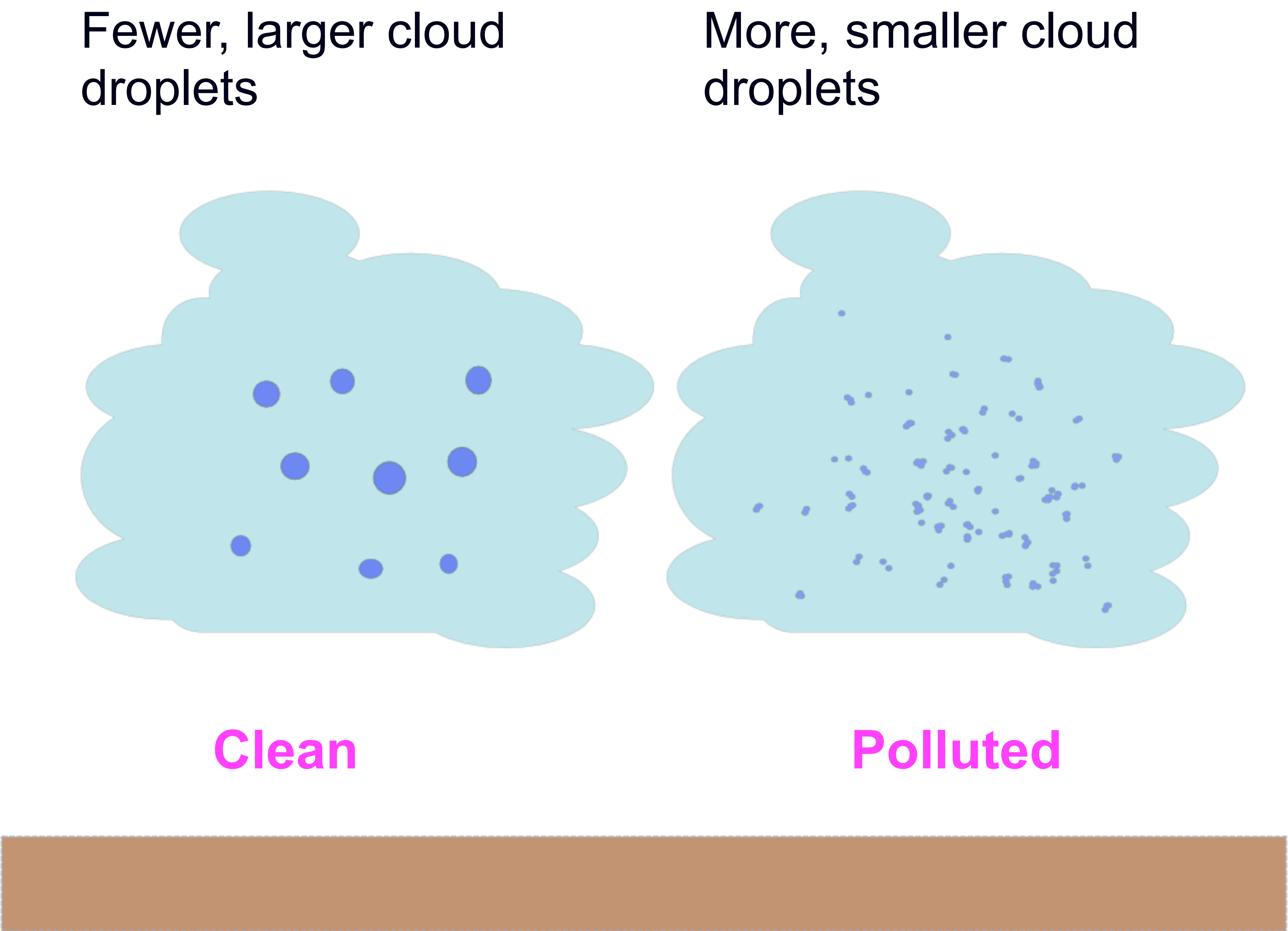
- Relative humidity
- Wind shear
- Aerosol indirect forcing


Aerosol Indirect Effects 101

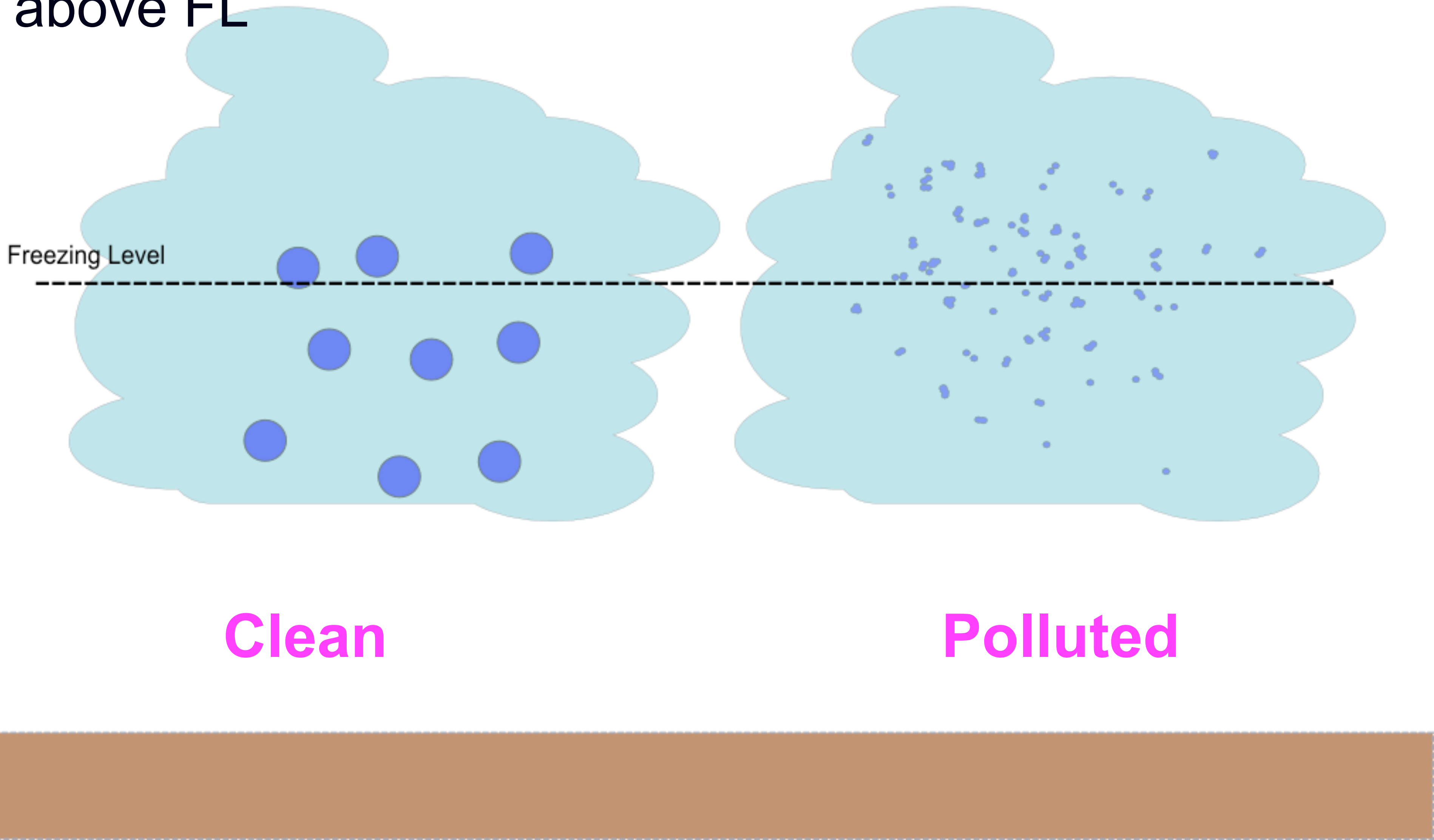


Clean **Polluted**

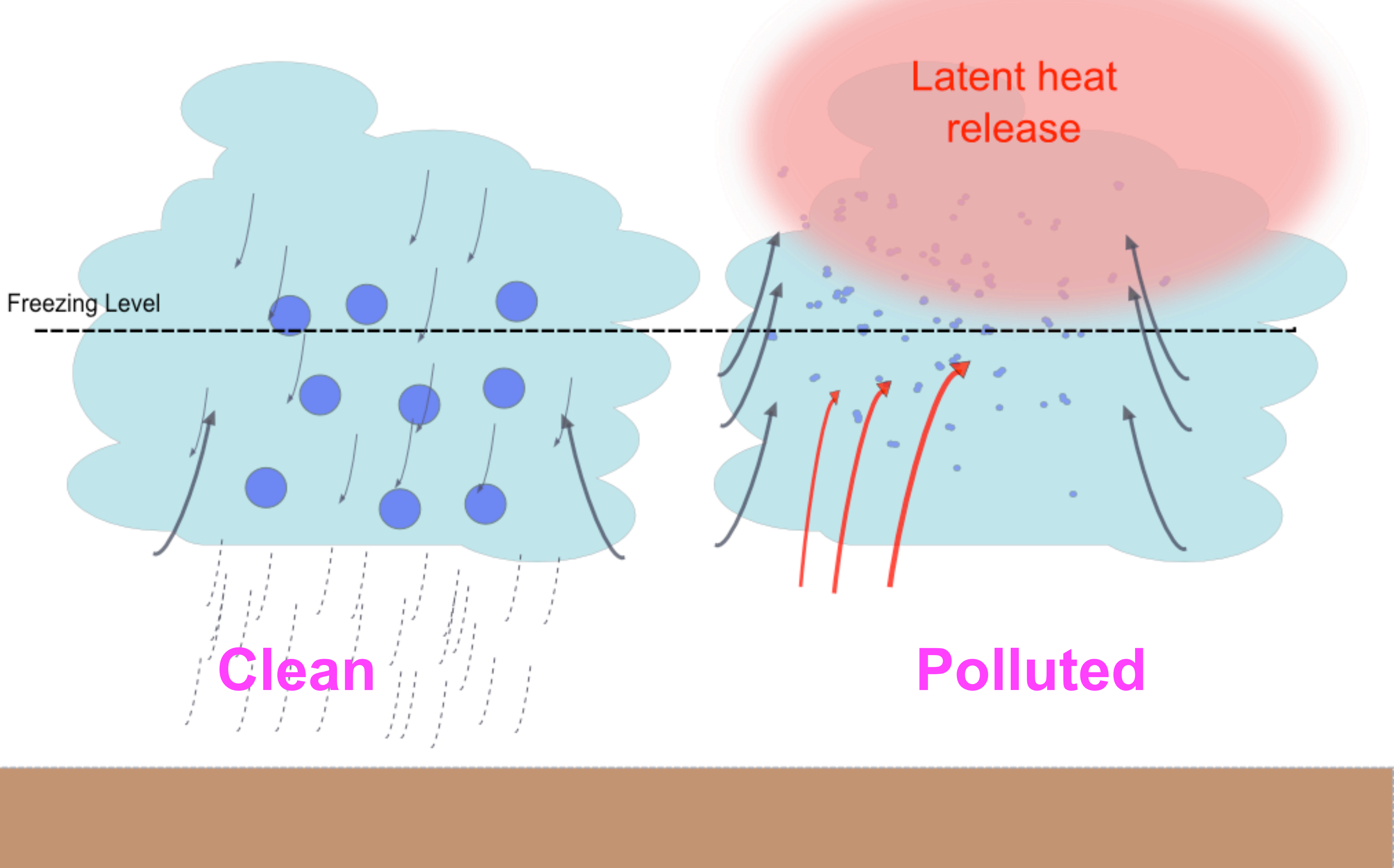
Figure Credit: Geoff Krall


Fewer, larger cloud droplets
More, smaller cloud droplets
Clean
Polluted

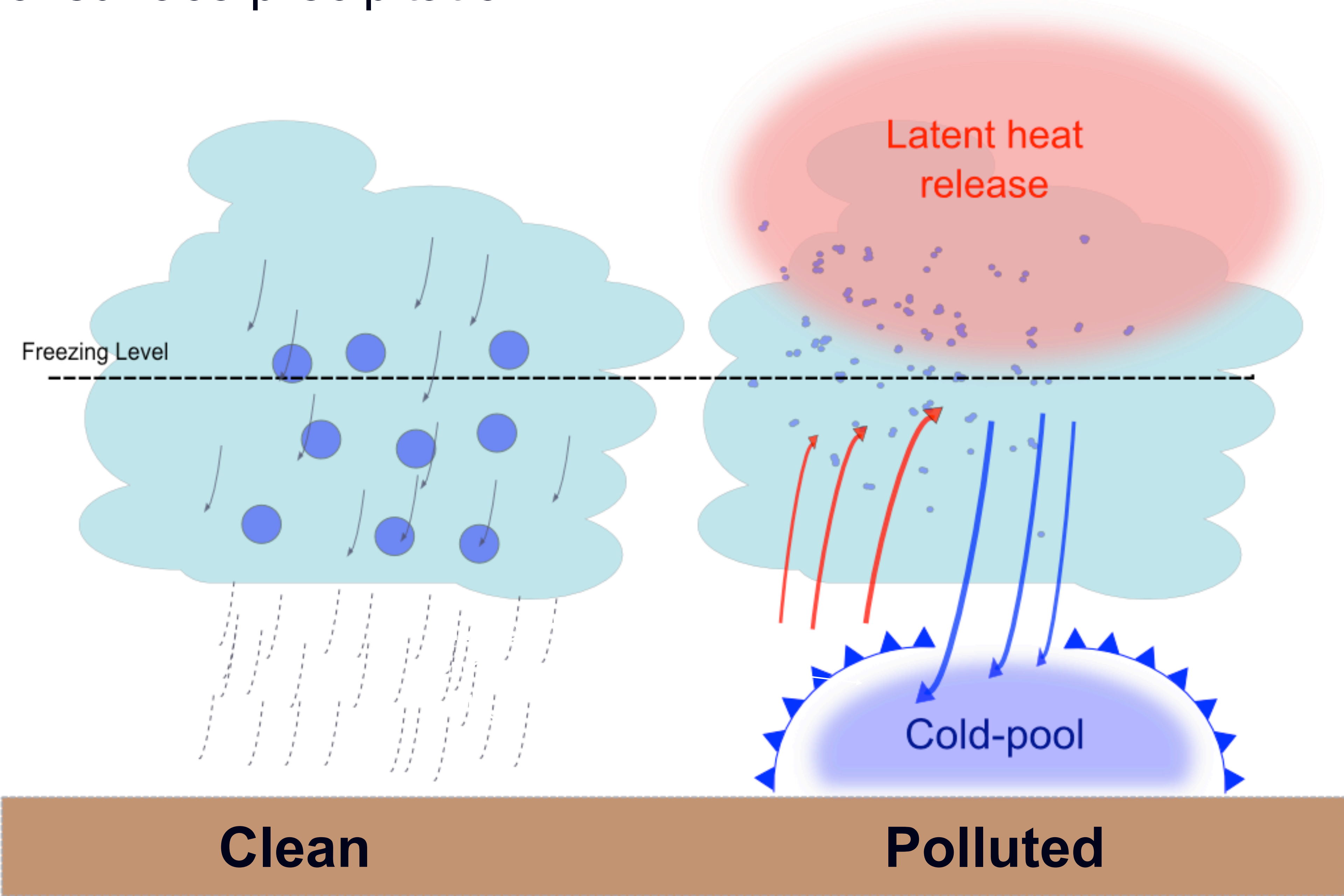
More efficient warm rain process
=> more rain at surface and less
cloud water available for lofting
above FL



Suppressed collection => more cloud water lofted => freezes and releases lh

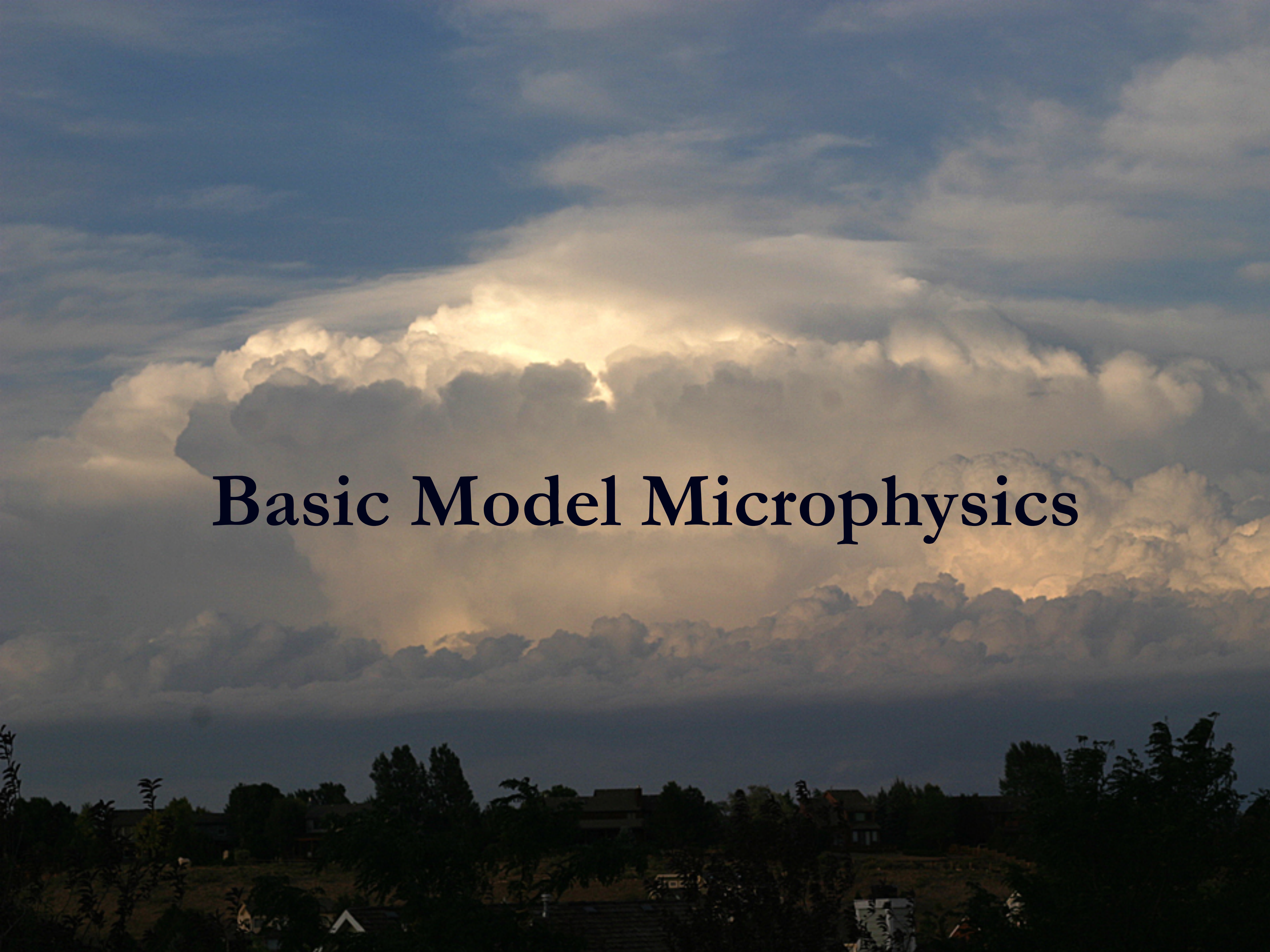


Cold pool impacts through effects on amount and nature of surface precipitation



Summary

- Aerosol indirect theory suggests that in polluted cases:
  - reduced collision-coalescence processes
  - reduced surface precipitation
  - less ice mass
  - weaker updrafts
  - stronger cold pools
- Not always the case with deep convection!


Basic Model Microphysics

Cloud Resolving Model

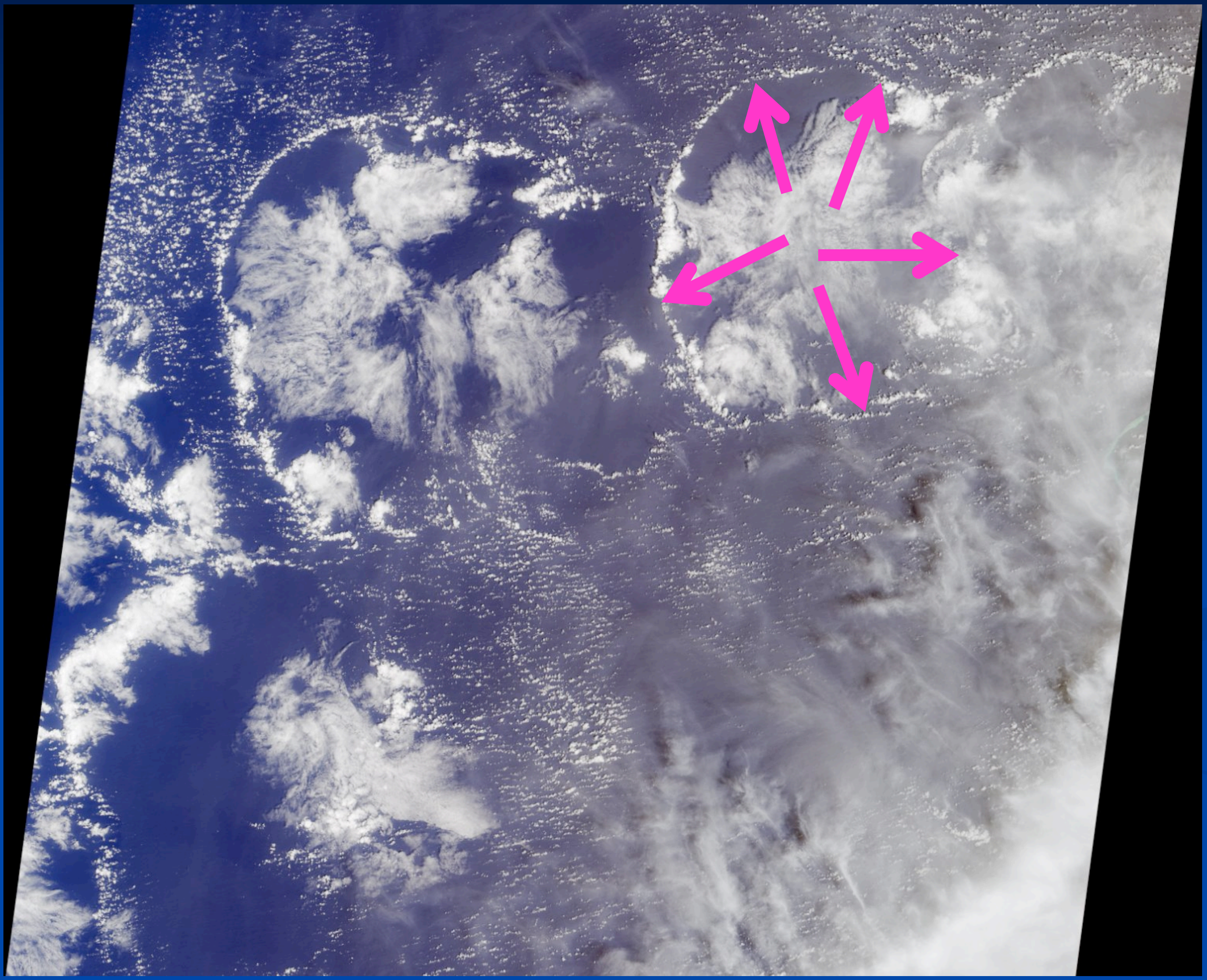
- RAMS model developed at CSU
- 2 Moment bin-emulating bulk microphysics
- Prognostic aerosol scheme (Saleeby and Cotton, 2004)

$$N_{activated} = N_{available} F_{activation}$$

- Cloud droplets are nucleated from CCN as a function of temperature, w, CCN number concentrations and aerosol mean diameter


Cold Pools

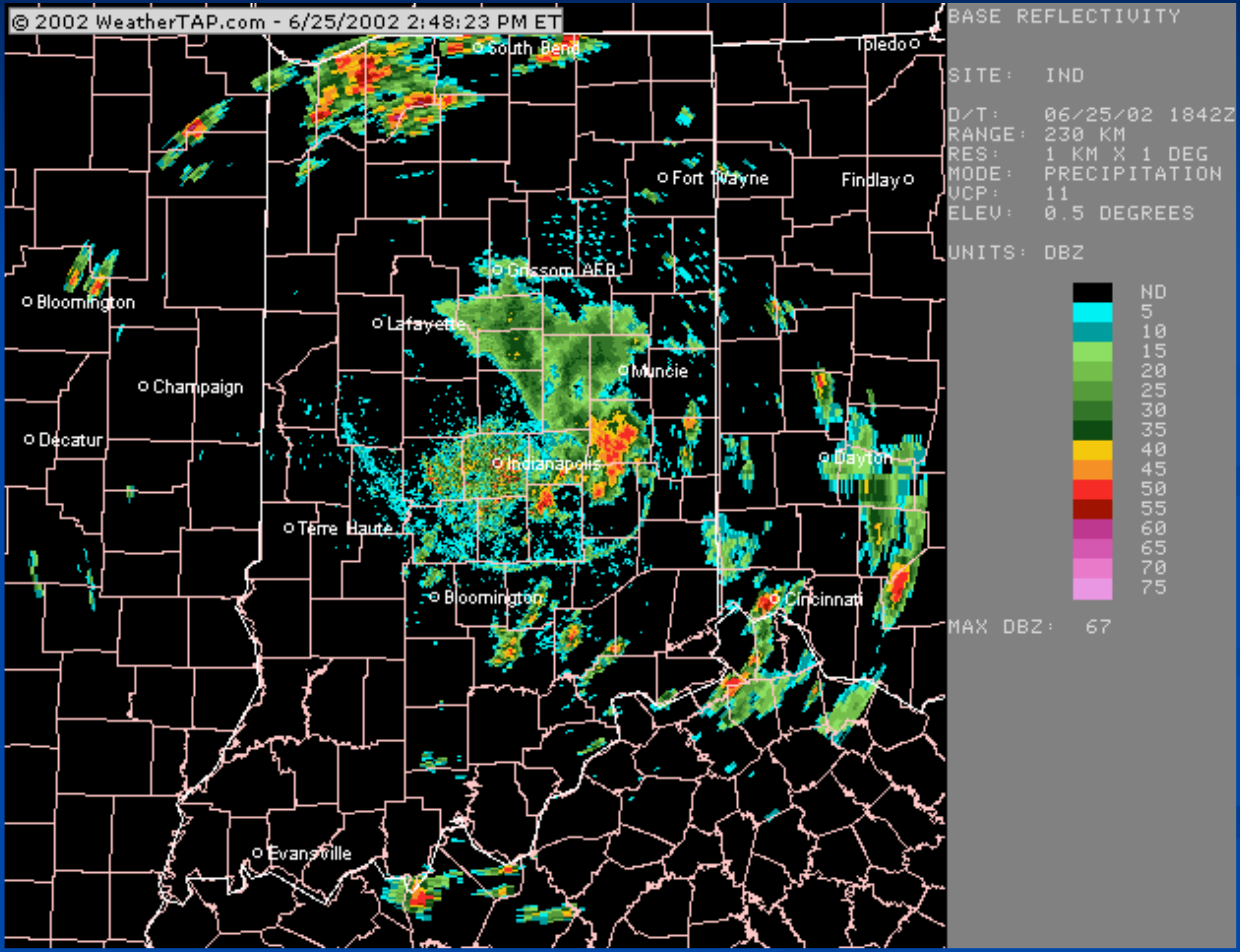
Cold Pools



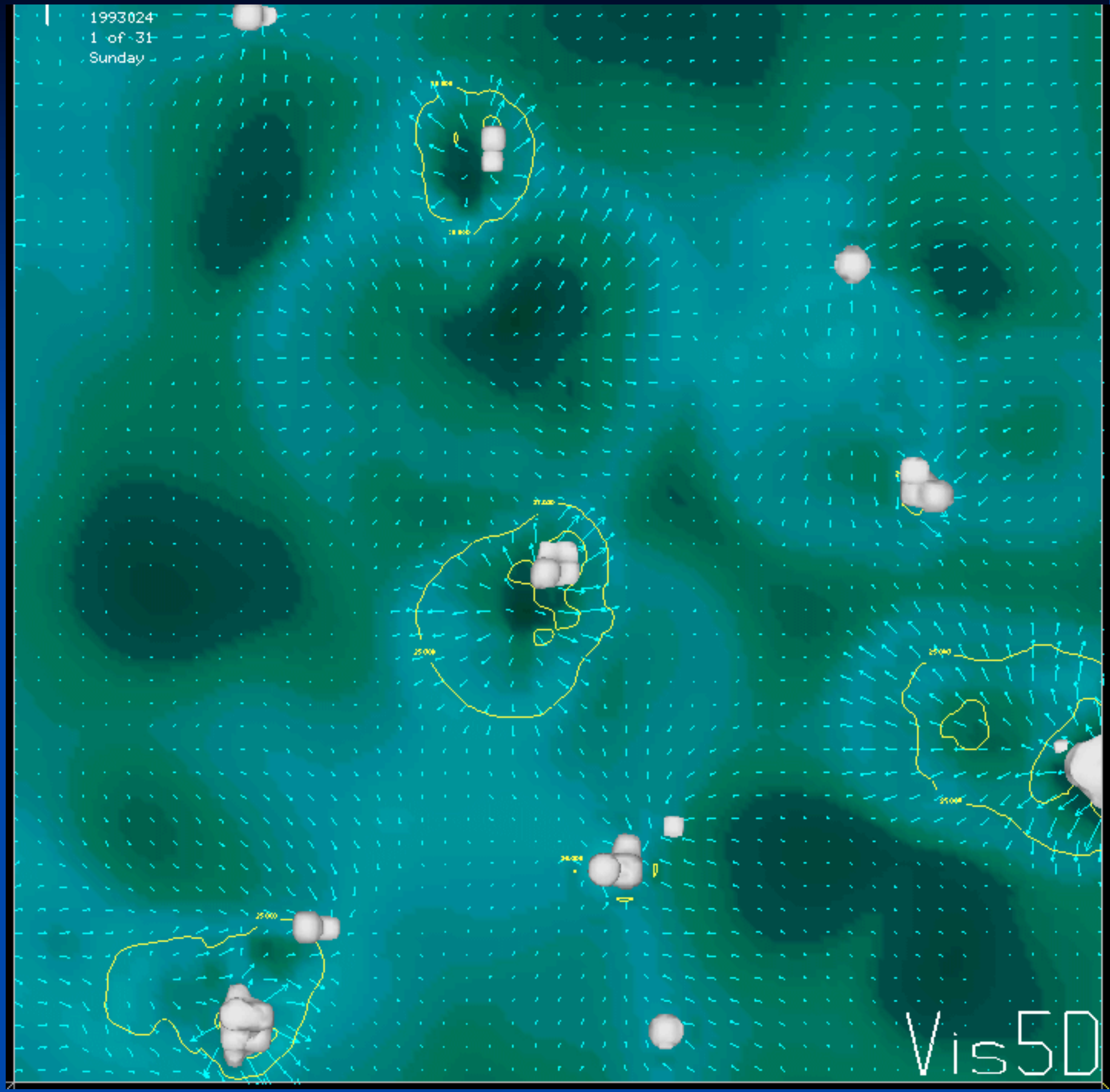
Satellite imagery of ocean tropical cold pools and their associated outflow boundaries (Image courtesy of NASA/GSFC/LaRC/JPL, MISR Team)

- Evaporatively – generated cold pools
- Susceptible to size distributions and hence aerosol indirect forcing

Cold Pools and Outflow Boundaries



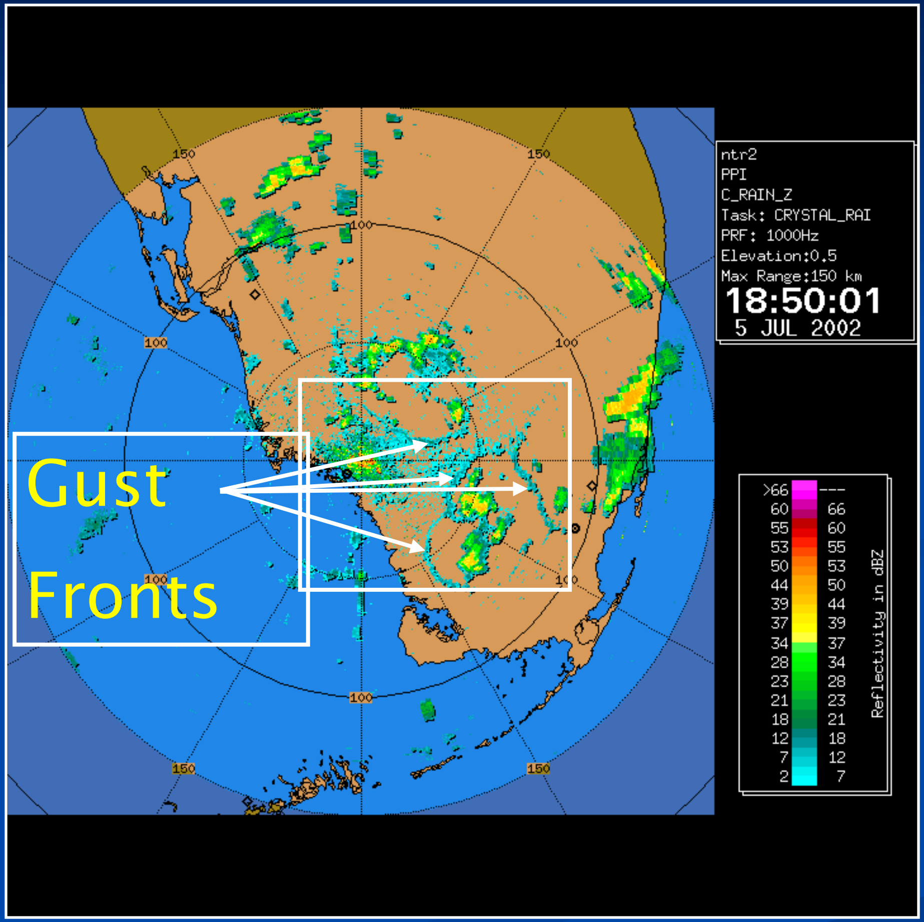
RCE Cold Pools



Cloud water mixing ratio (white, 1.5 g kg^{-1} isosurface); water vapor mixing ratio (color; 15-19 g kg^{-1}); temperature (yellow contours); and wind vectors at 20m AGL

Cold Pools during CRYSTAL-FACE

- The colder the cold pool the faster the gust front travels
- Long-lived storms when the updraft co-located with gust front

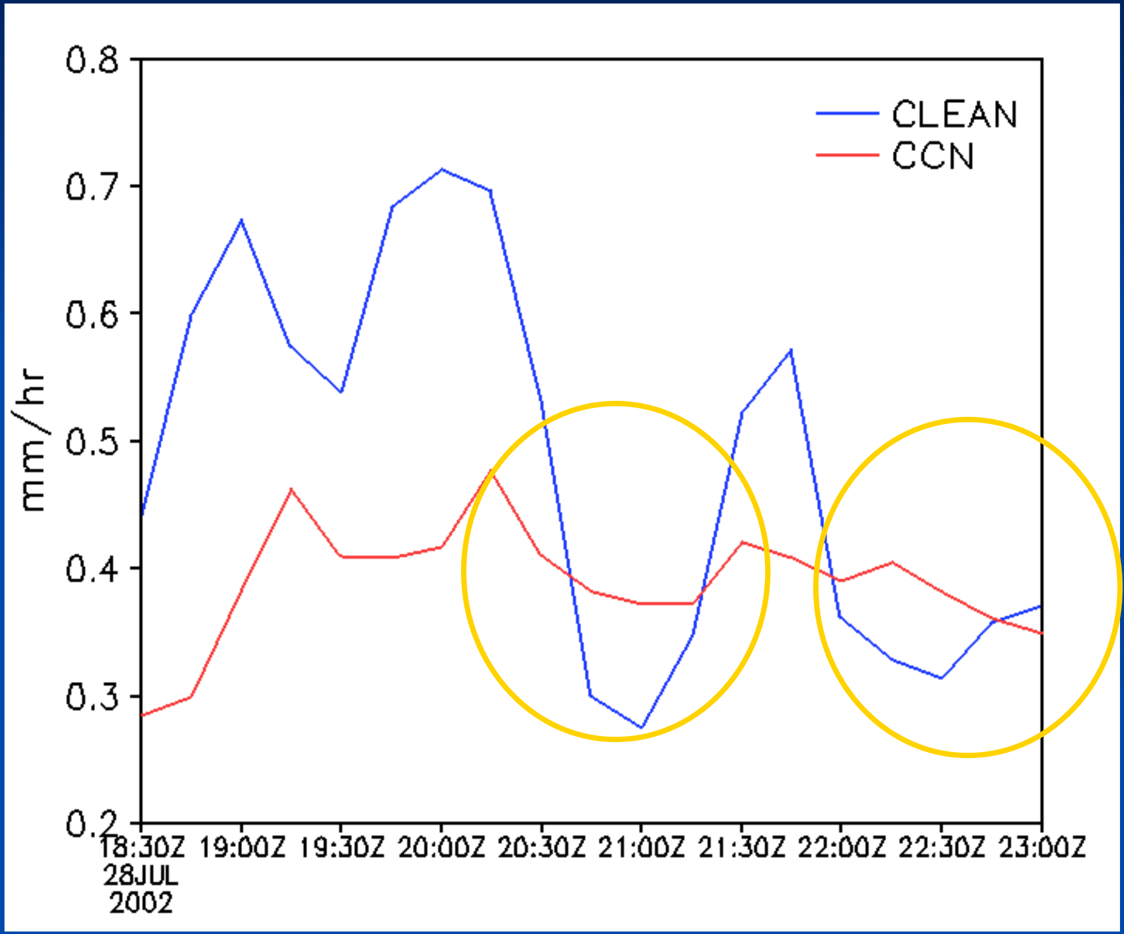


Radar image demonstrating gust fronts observed during CRYSTAL-FACE (Frank and Kucera 2003)

Model and Experiment Setup

- During this field campaign – outbreak of Saharan dust => providing opportunities for examining storm development in clean and dusty conditions
- 12 hour simulations of storm development observed over Florida during NASA's CRYSTAL-FACE field campaign
- 4 nested grids with 500m grid spacing on grid 4
- Aerosol initialization representing clean and dusty / polluted conditions observed during campaign

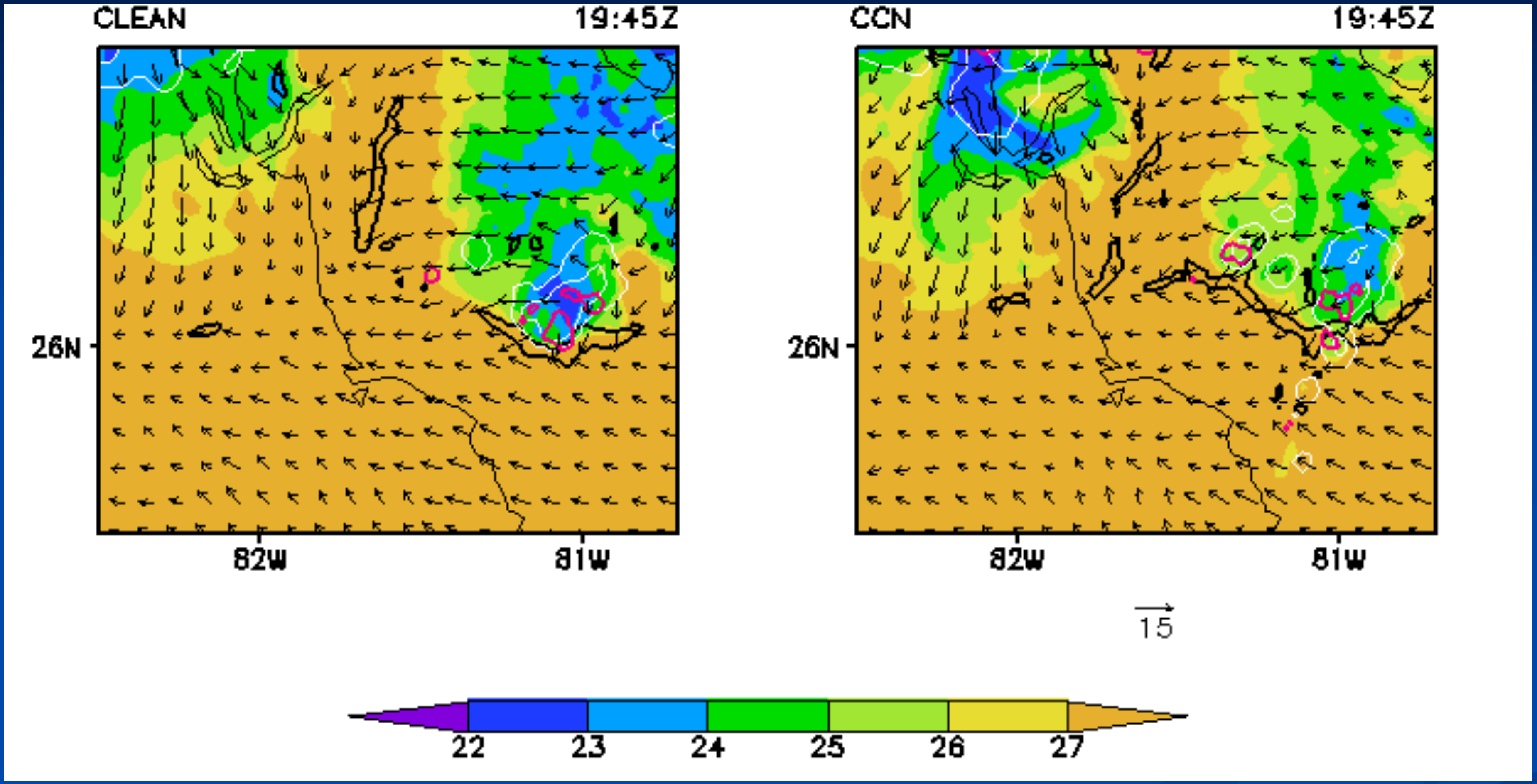
Precipitation Rates



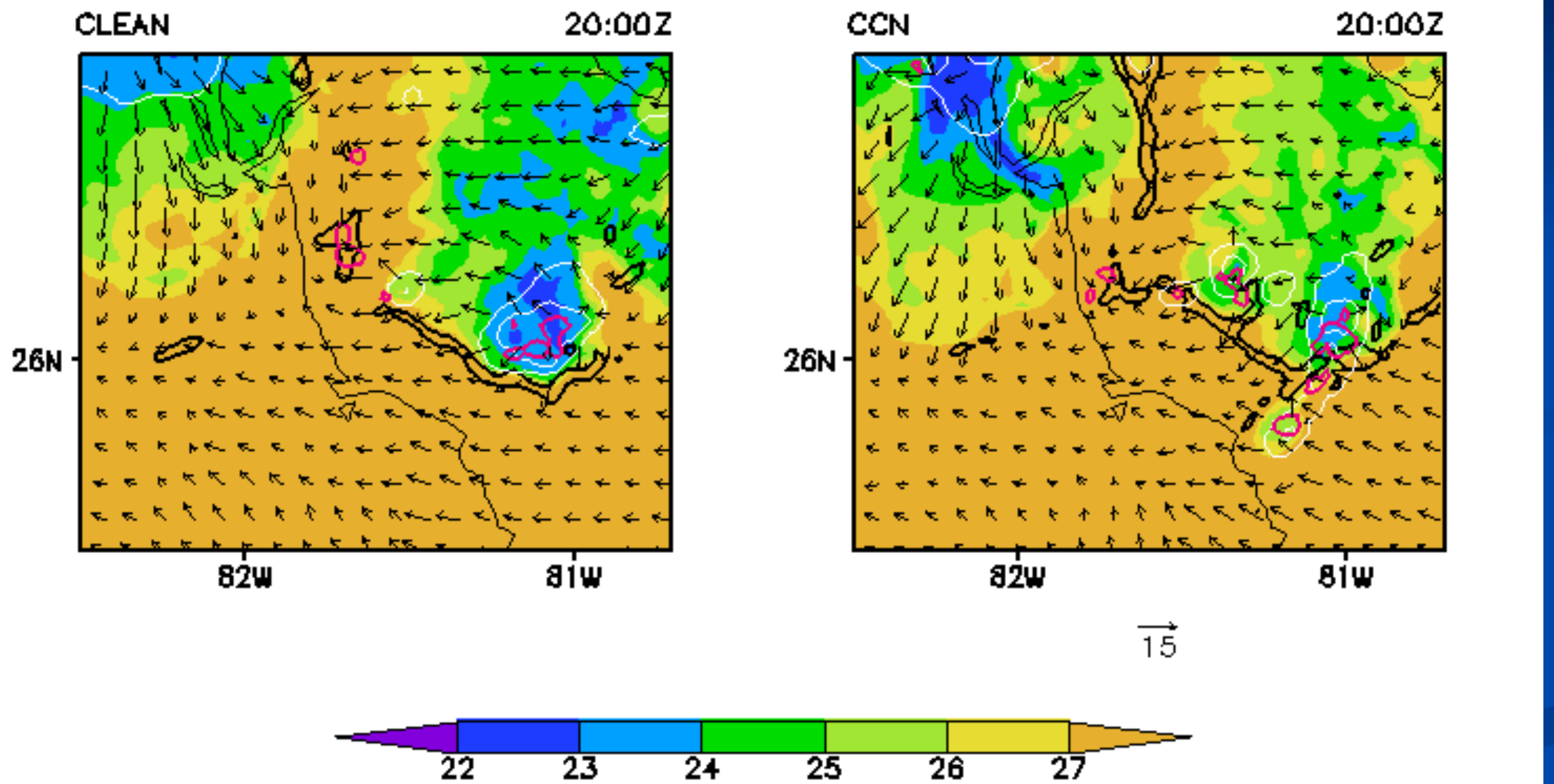
Time series of horizontally-averaged precipitation rates (mm/hr) (van den Heever, 2012 in review)

- Enhanced CCN concentrations:
  - Overall reduced surface precipitation => in keeping with aerosol indirect forcing
  - More consistent precipitation production with greater rates at times

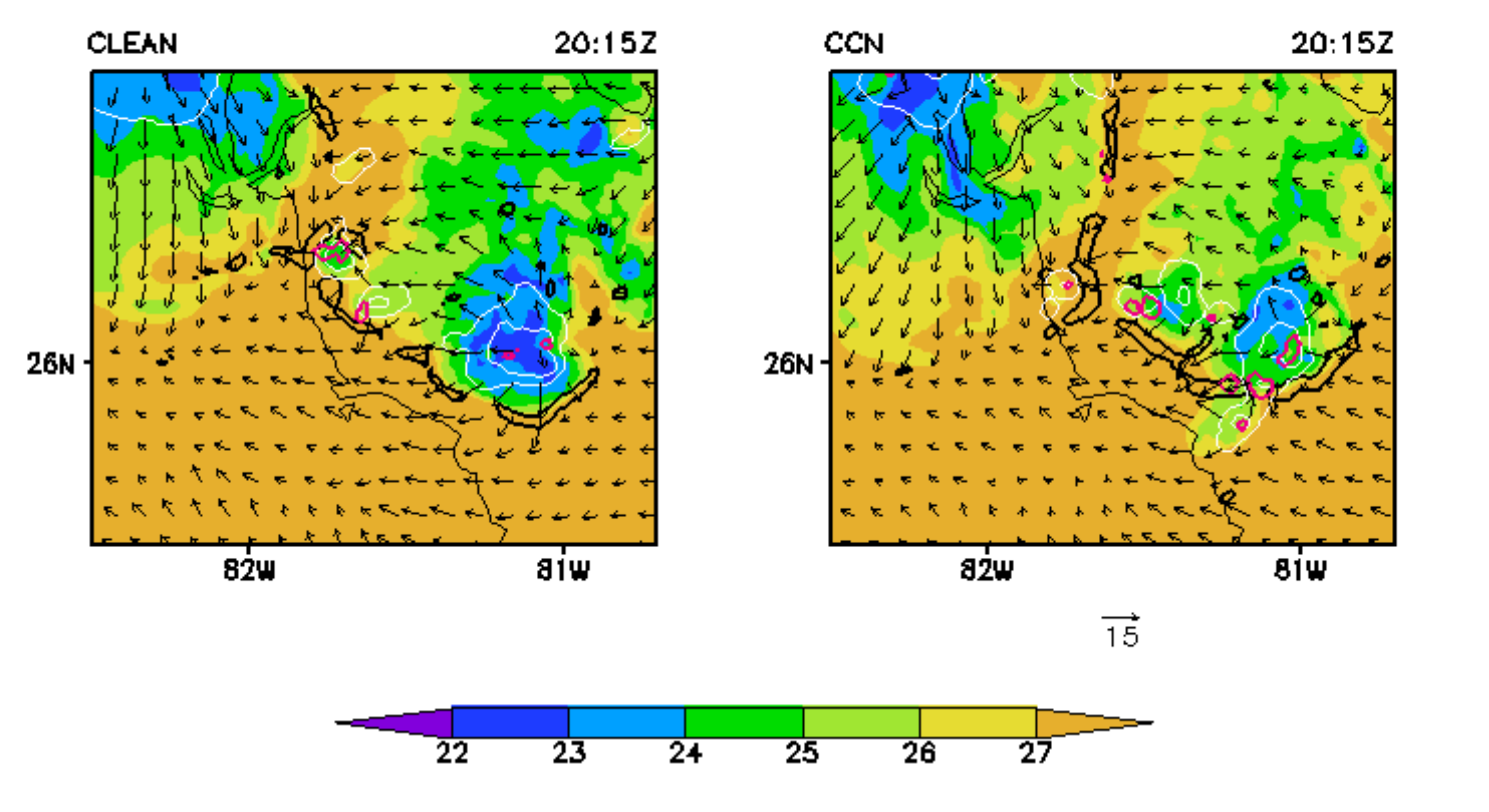
Storm and Cold Pool Development



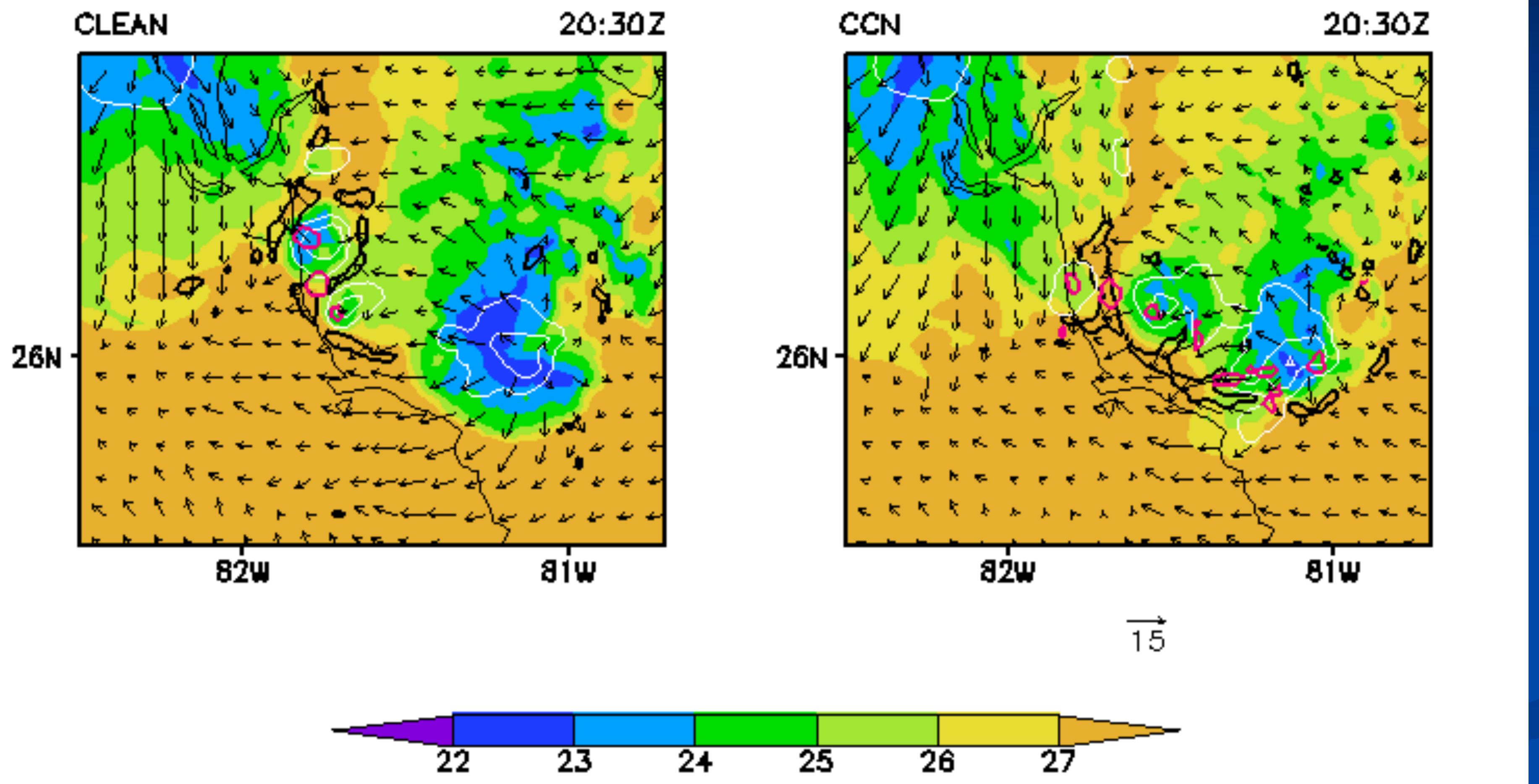
Surface temperature (°C, colored), precipitation rates (white, 1 and 10 mm hr^{-1} isolines shown), updrafts at 5.6km AGL (pink, 5 ms^{-1} isoline shown), convergence (thick black, 0.0015 s^{-1} isoline shown), coastline of west coast of Florida (thin black), and wind vectors (van den Heever, 2012 in review)



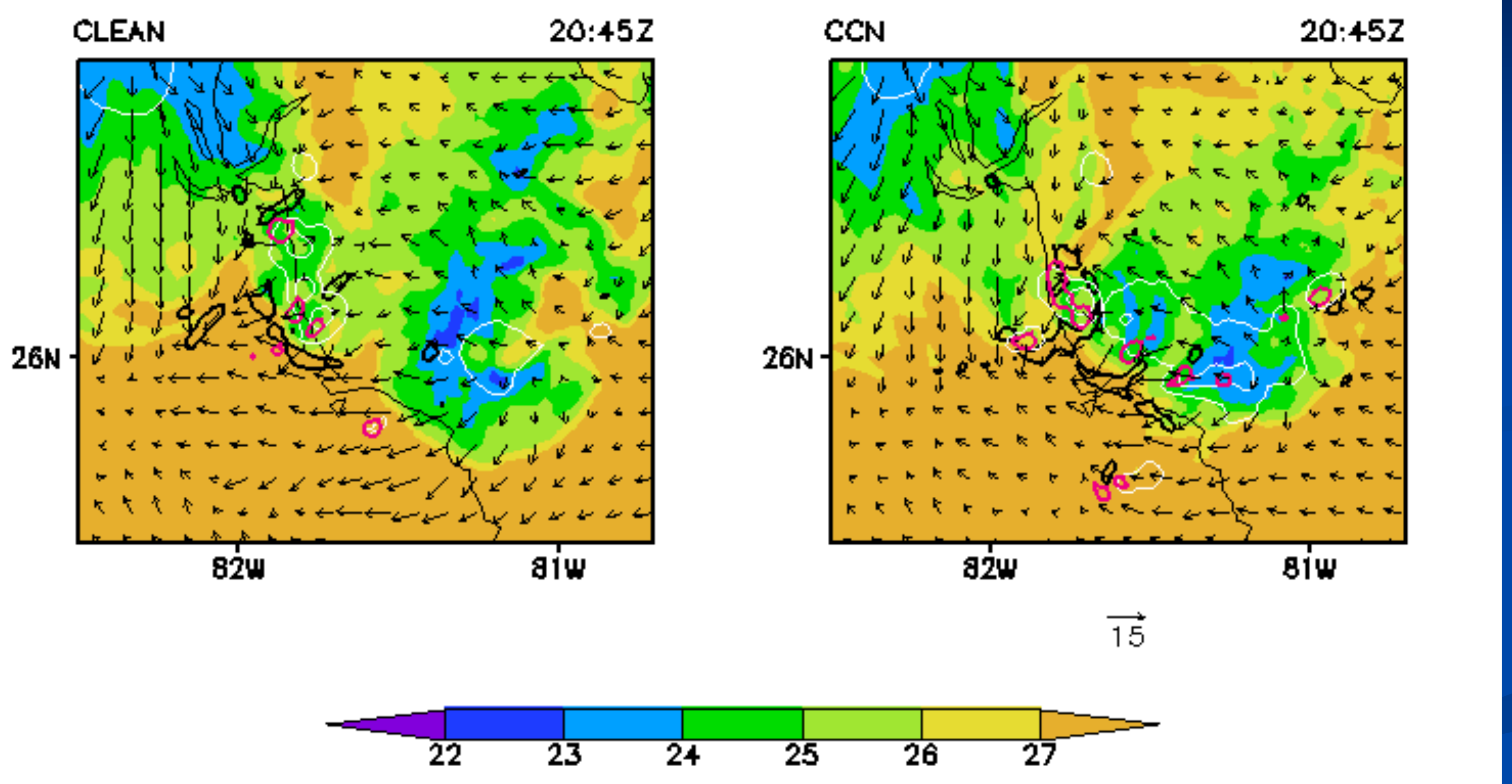
CLEAN
20:00Z
CCN
20:00Z
26N
82W
81W
15
22
23
24
25
26
27

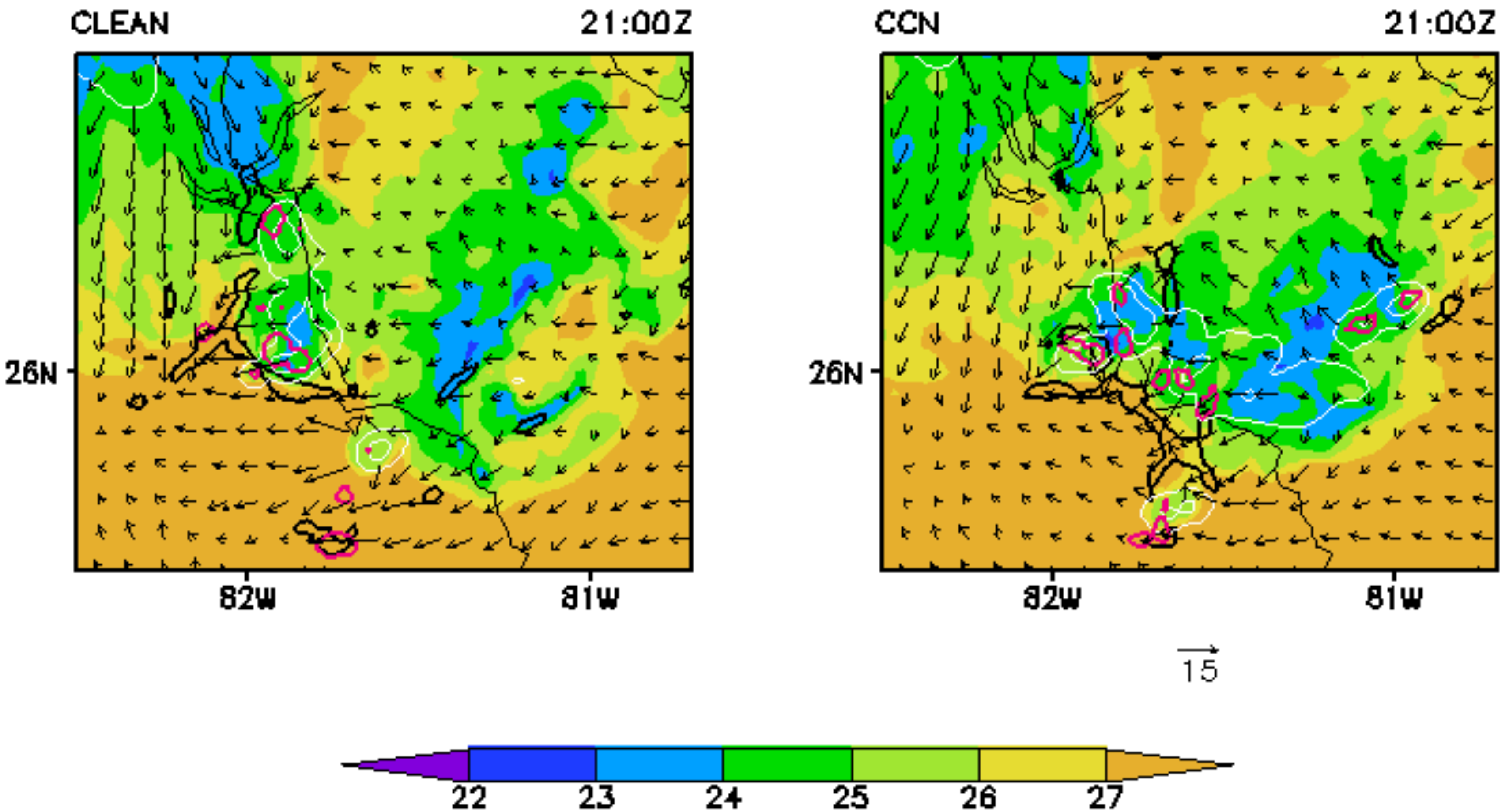


CLEAN
20:15Z
26N
82W
81W
CCN
20:15Z
26N
82W
81W
15
22
23
24
25
26
27



CLEAN
20:30Z
CCN
20:30Z
26N
82W
81W
15
22
23
24
25
26
27


CLEAN
20:45Z
CCN
20:45Z
26N
82W
81W
15
22
23
24
25
26
27


CLEAN
21:00Z
CCN
21:00Z
26N
82W
81W
15
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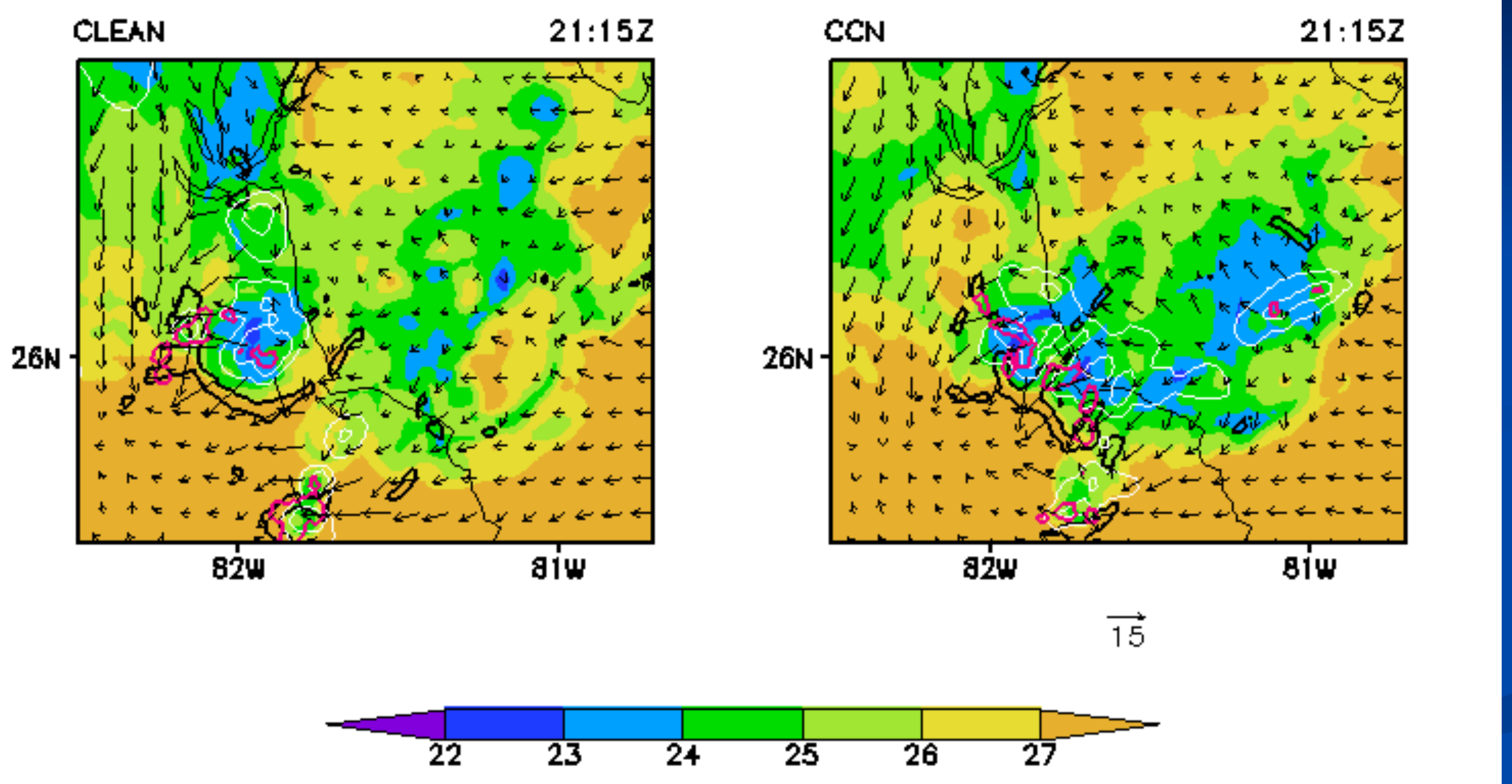
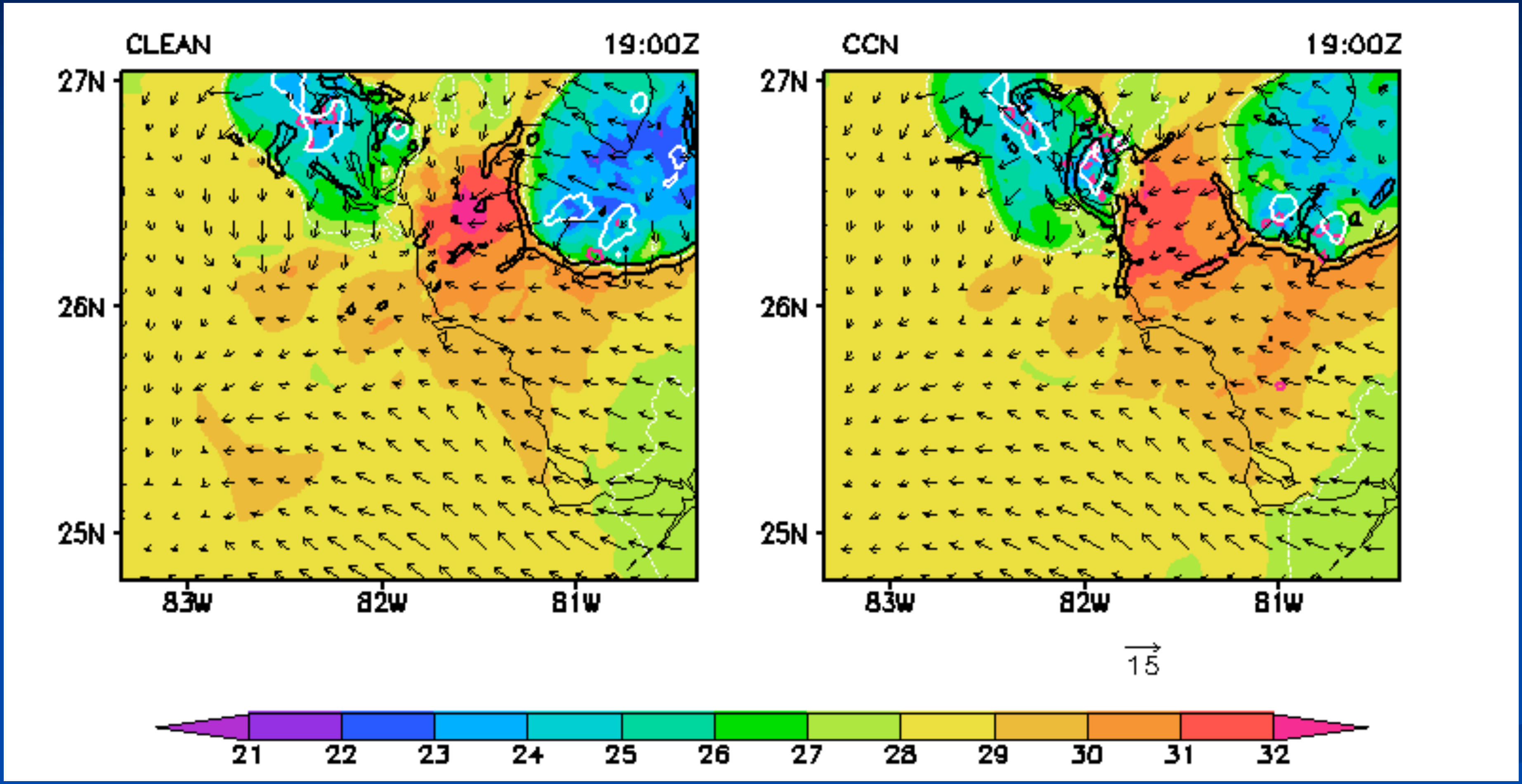
27

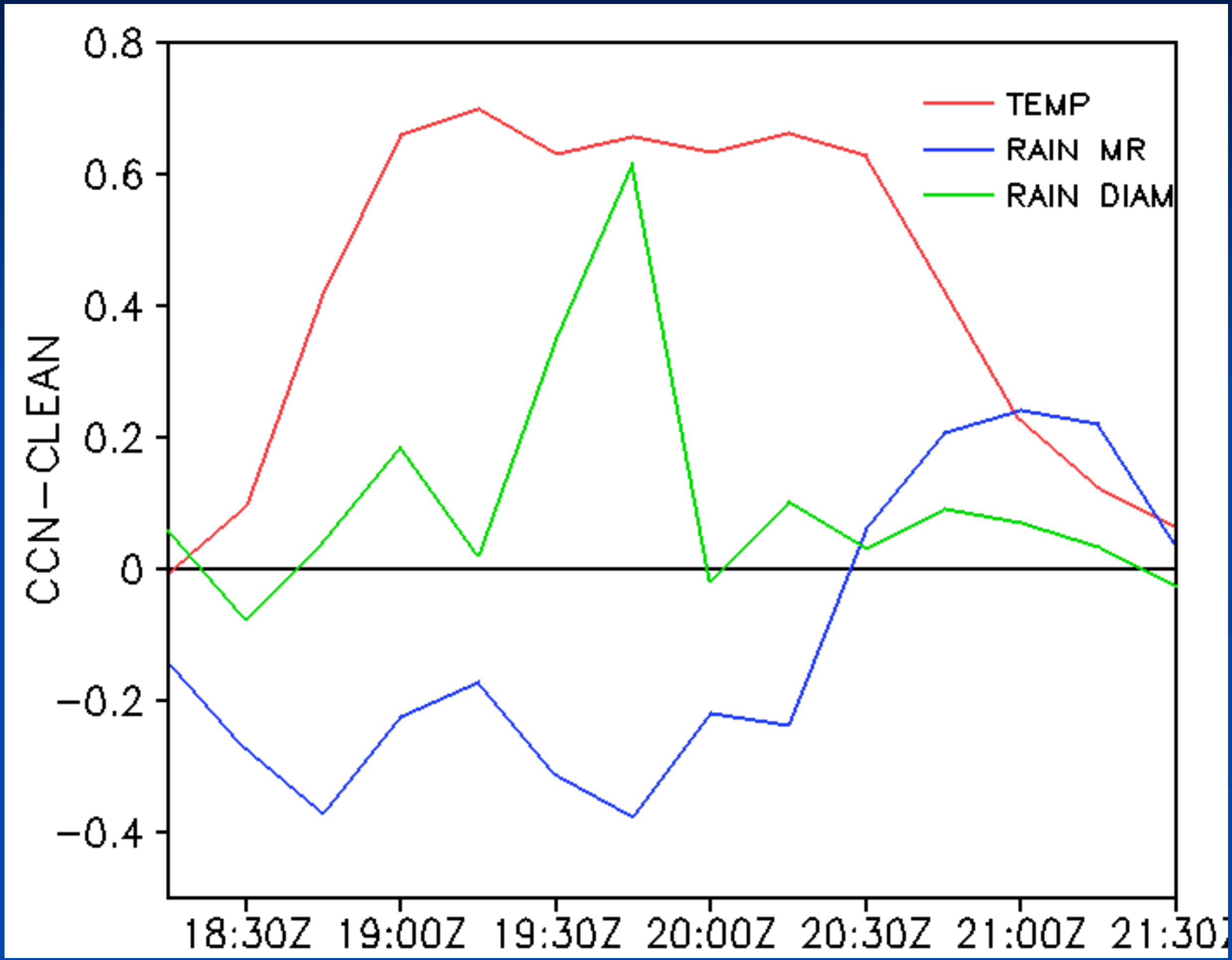

CLEAN
21:15Z
CCN
21:15Z
26N
82W
81W
15
22
23
24
25
26
27

CLEAN DUSTY



CLEAN
19:00Z
CCN
19:00Z
27N
26N
25N
83W
82W
81W
15
21
22
23
24
25
26
27
28
29
30
31
32

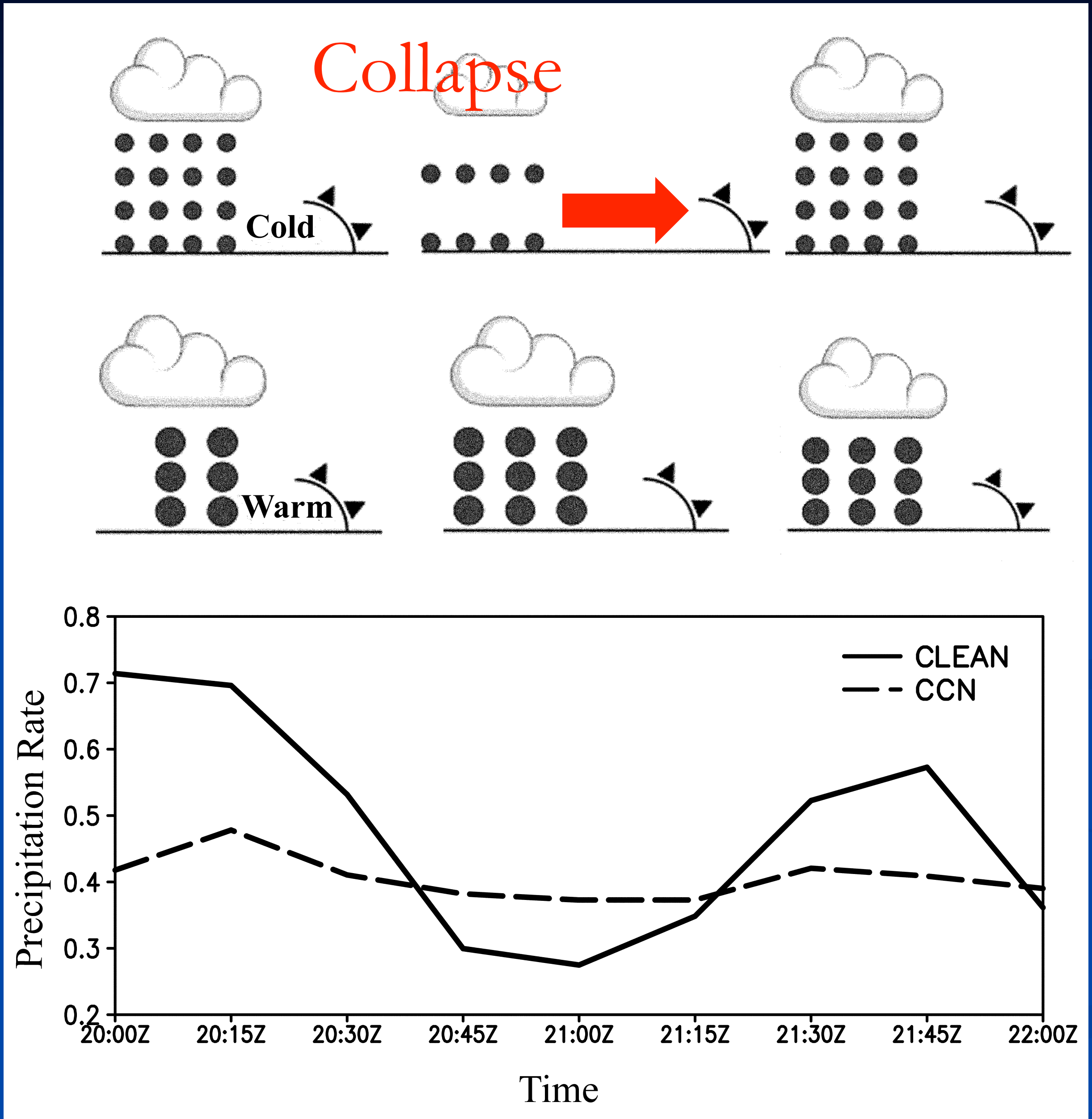
Lower-Level Characteristics



Time series of CCN-CLEAN horizontally-averaged surface temperature (red), near surface rain mixing ratios (blue) and rain mean diameters (green) (van den Heever, 2012 in review)

High CCN:

- weaker / warmer cold pools
- reduced rain mixing ratios - suppressed warm rain process
- greater raindrop diameters



Clean

Polluted

Precipitation

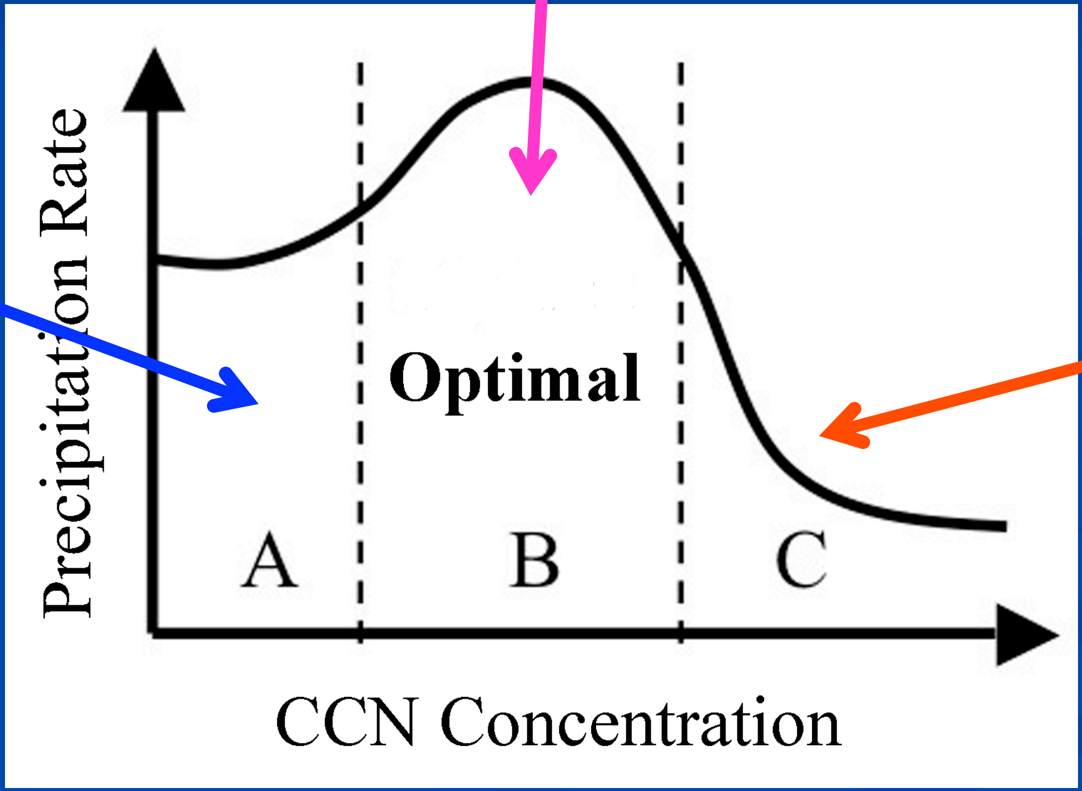
(van den Heever, 2012 in review)

"Optimal" Aerosol Concentrations

Just right – balance between rainfall and cold pool forcing

Too few – cold pool run away

Too many – rainfall suppression



Cold Pool Summary

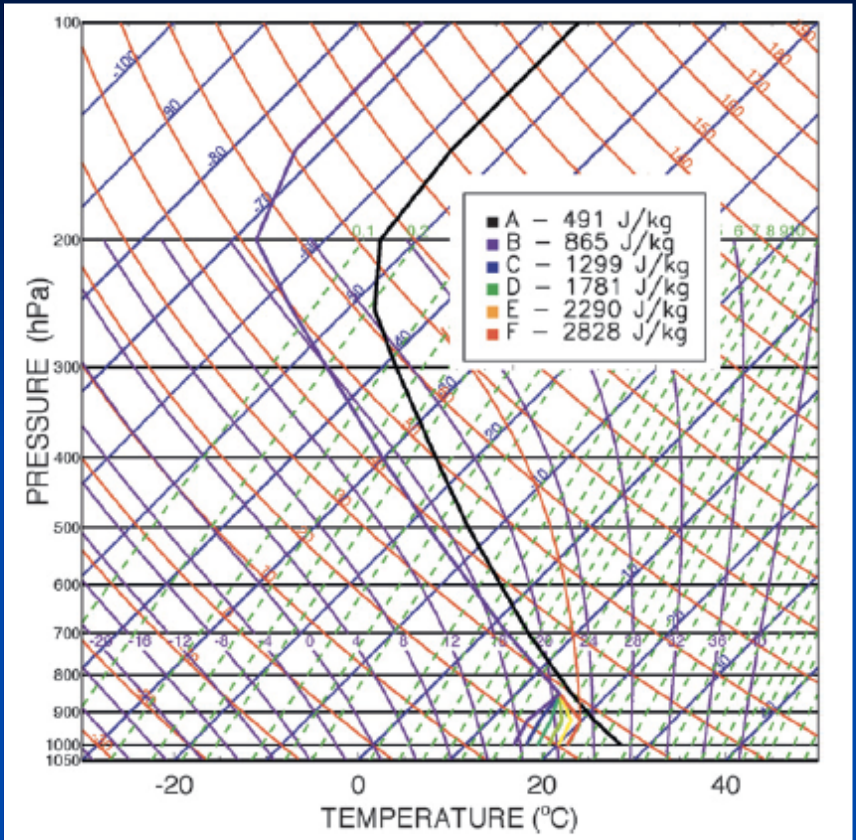
- Aerosol impacts on cold pool forcing may **offset** aerosol suppression of surface precipitation
- There may be an ideal amount of aerosol that produces maximum surface precipitation over the lifetime of the storm
- Highly nonlinear response once secondary convection produced


Role of Environment

Aerosol versus CAPE

Seibert, CO LP supercell   Photos: Brian McNoldy

Supercell Simulations

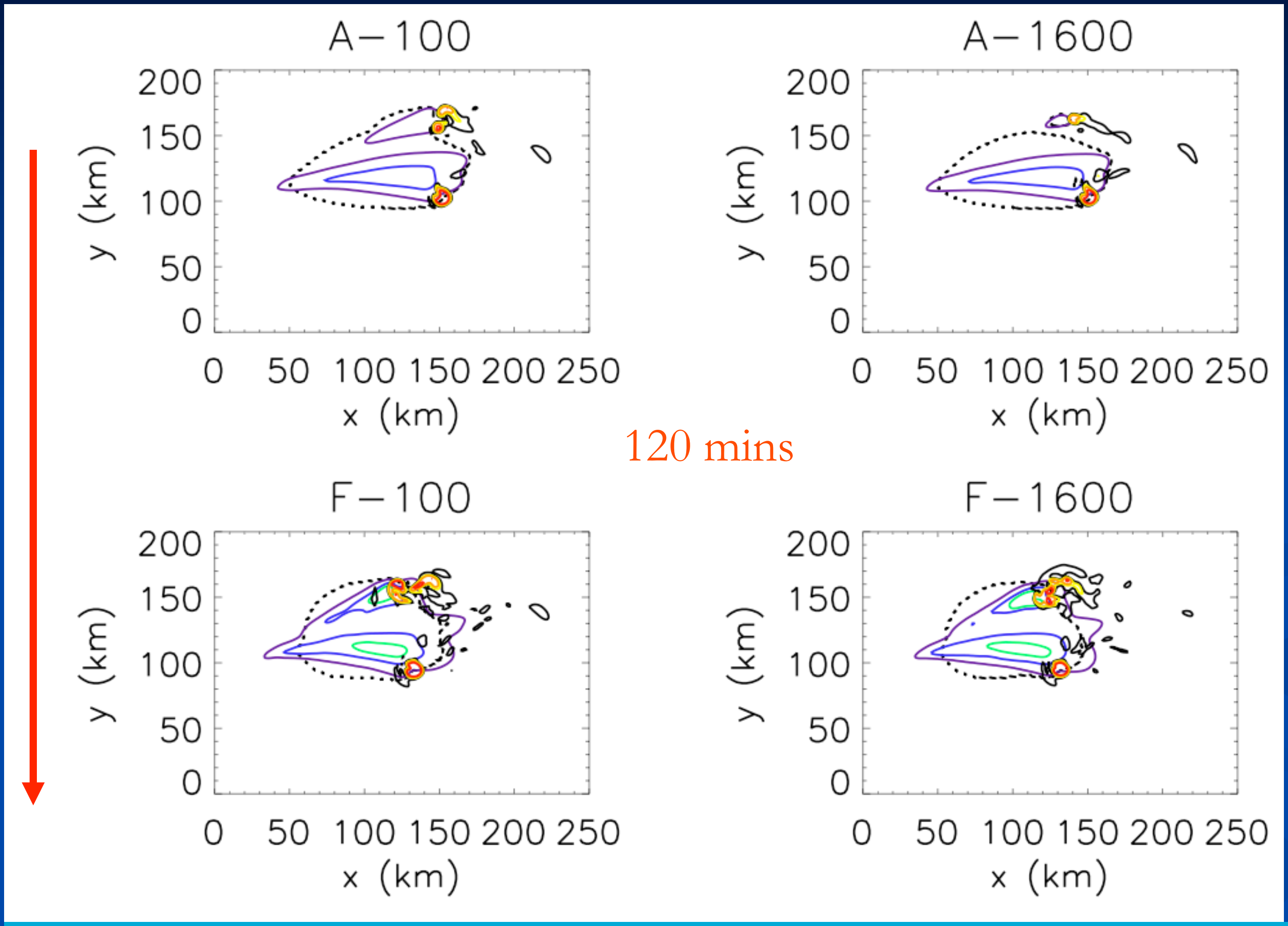


- Experiments in which CAPE and aerosol concentrations were varied
- WK sounding
- CAPE values from 491 to 2828 J/kg ~6 times increase

CAPE ($J\ kg^{-1}$)	N (cm^{-3}) 100	200	400	800	1600
491	A-100	A-200	A-400	A-800	A-1600
865	B-100	B-200	B-400	B-800	B-1600
1299	C-100	C-200	C-400	C-800	C-1600
1781	D-100	D-200	D-400	D-800	D-1600
2290	E-100	E-200	E-400	E-800	E-1600
2828	F-100	F-200	F-400	F-800	F-1600

Increasing CCN Concentrations

Increasing CAPE



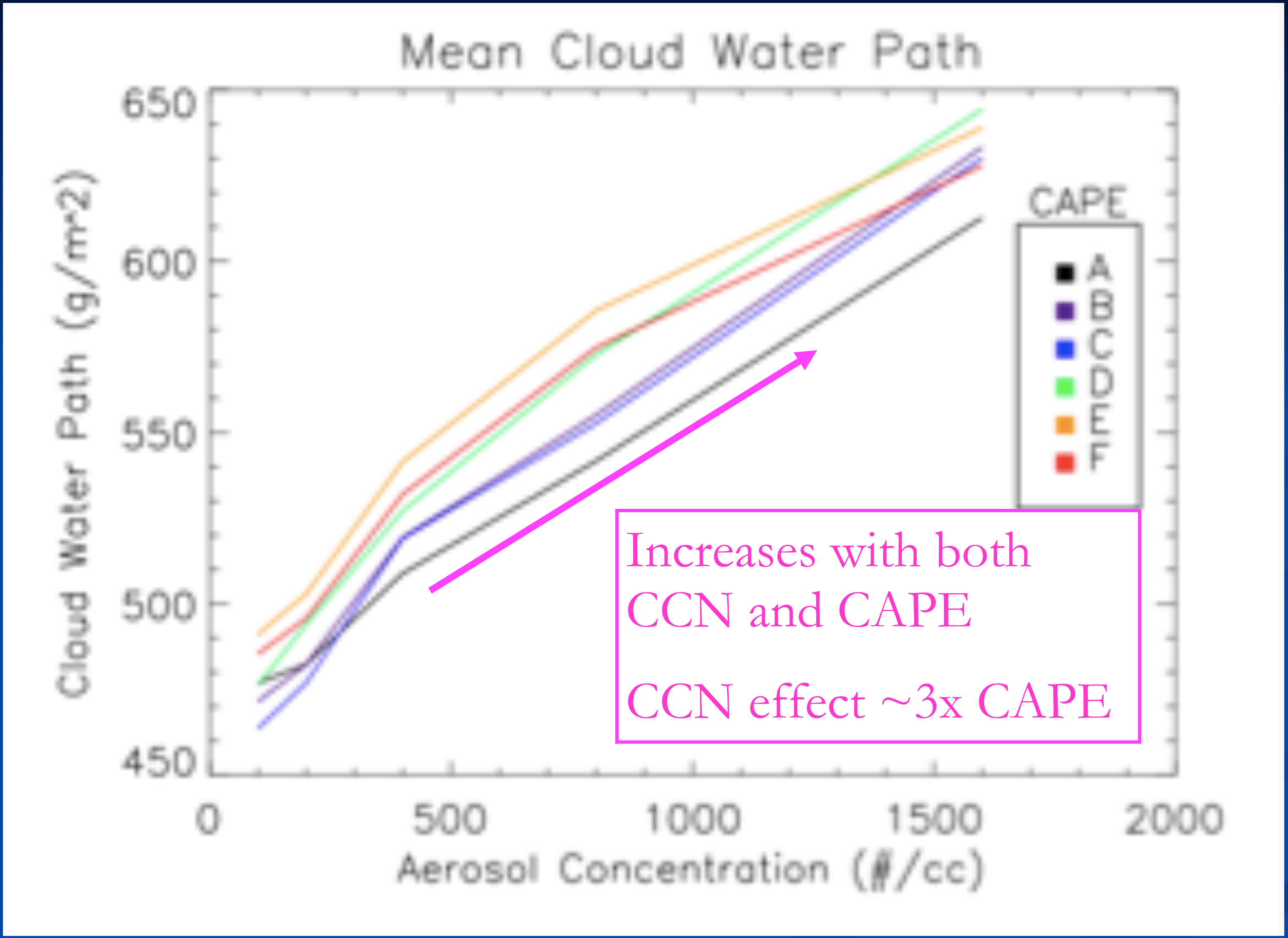
Delayed and reduced precipitation

Weak LM and secondary convection

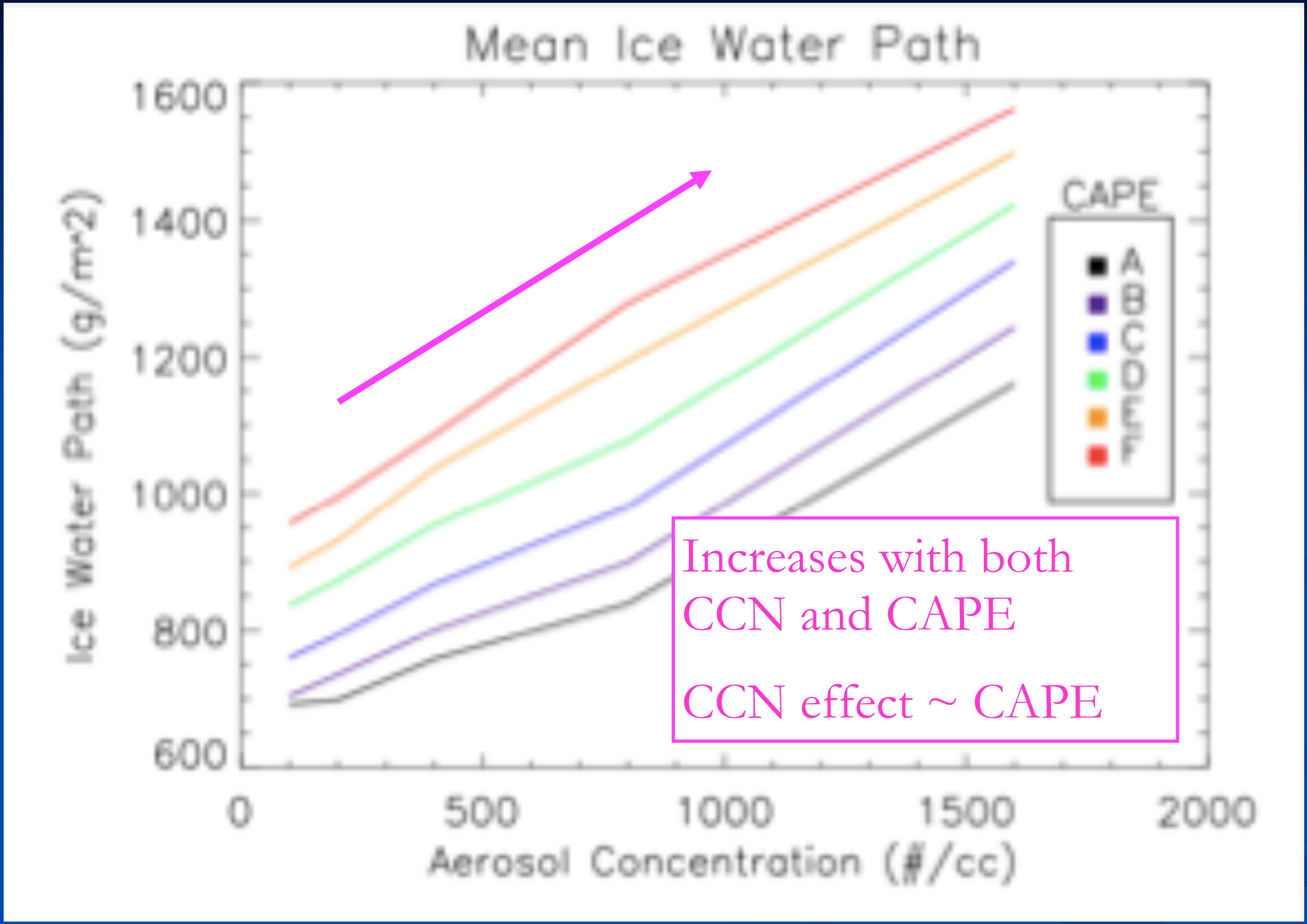
Reduced CCN effect on precipitation and organization

Surface Cold Pool: dotted line; W at 5.4 km: 5 m/s, 10 m/s, 20 m/s;
Surface Precipitation: 1 mm, 10 mm, 20 mm

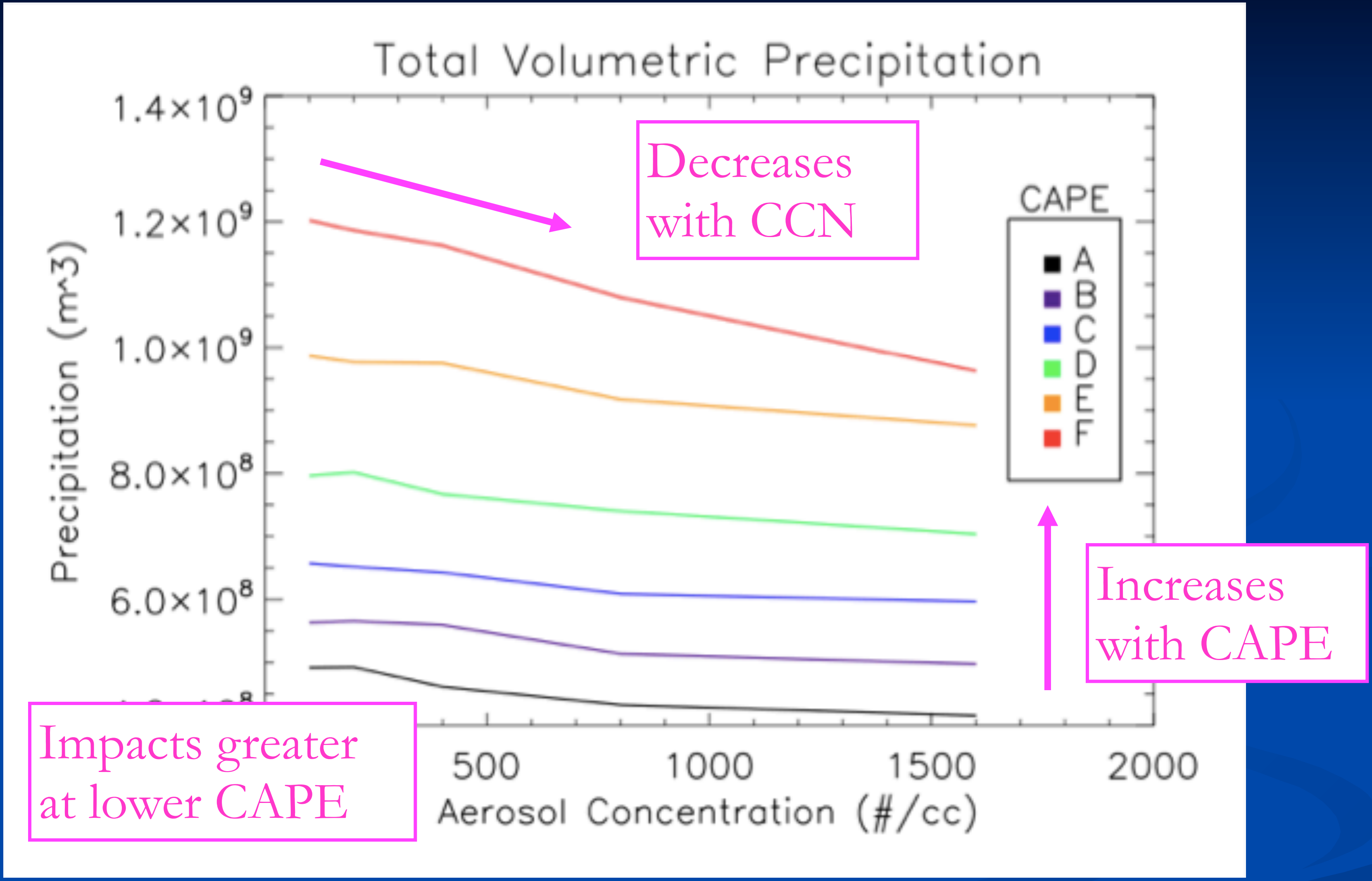
Storm organization at 120 mins as a function of CCN and CAPE (after Storer, van den Heever and Stephens, 2010)



Mean CWP as a function of CCN and CAPE (after Storer et al 2010)



Mean IWP as a function of CCN and CAPE (after Storer et al 2010)



Accumulated precipitation as a function of CCN and CAPE (after Storer et al 2010)

CAPE vs Aerosol Summary

- Various storm attributes are affected differently by environmental and aerosol variations
- CAPE **modulates** the impacts of aerosol indirect forcing => with greater CAPE we tend to see relatively weaker aerosol indirect effects

Aerosol Environment

Mesoscale circulations contribute ~30% to global dust production (Miller et al 2008)

How Does Dust Ingestion Occur?

- Difficult problem to answer
  - Difficult to measure in situ
    - Harmful to aircraft engines
  - Many production mechanisms

Regime 1

Synoptic-scale lofting
(e.g. Saharan Air Layer)

Background dust

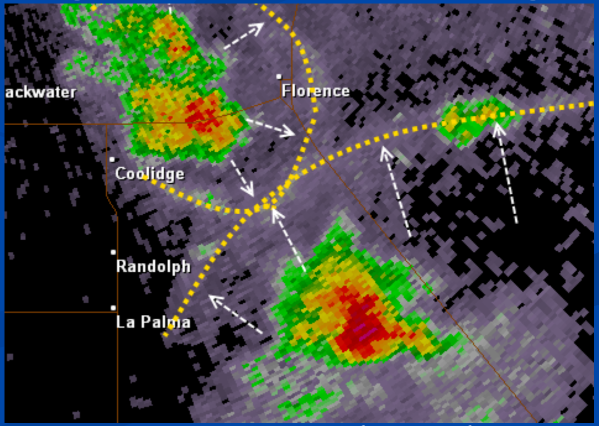
Regime 2

Mesoscale lofting
(e.g. Haboob dust storm)

Localized dust

Regime 3

Boundary lofting
(e.g. dust storms colliding)



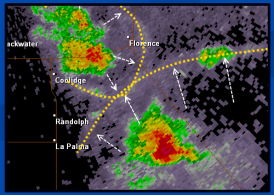
Localized and
complex dust

Methodology

- Three idealized numerical simulations of supercell within common dust regimes (Seigel and van den Heever, 2012)
  - Identical supercell evolution in each experiment

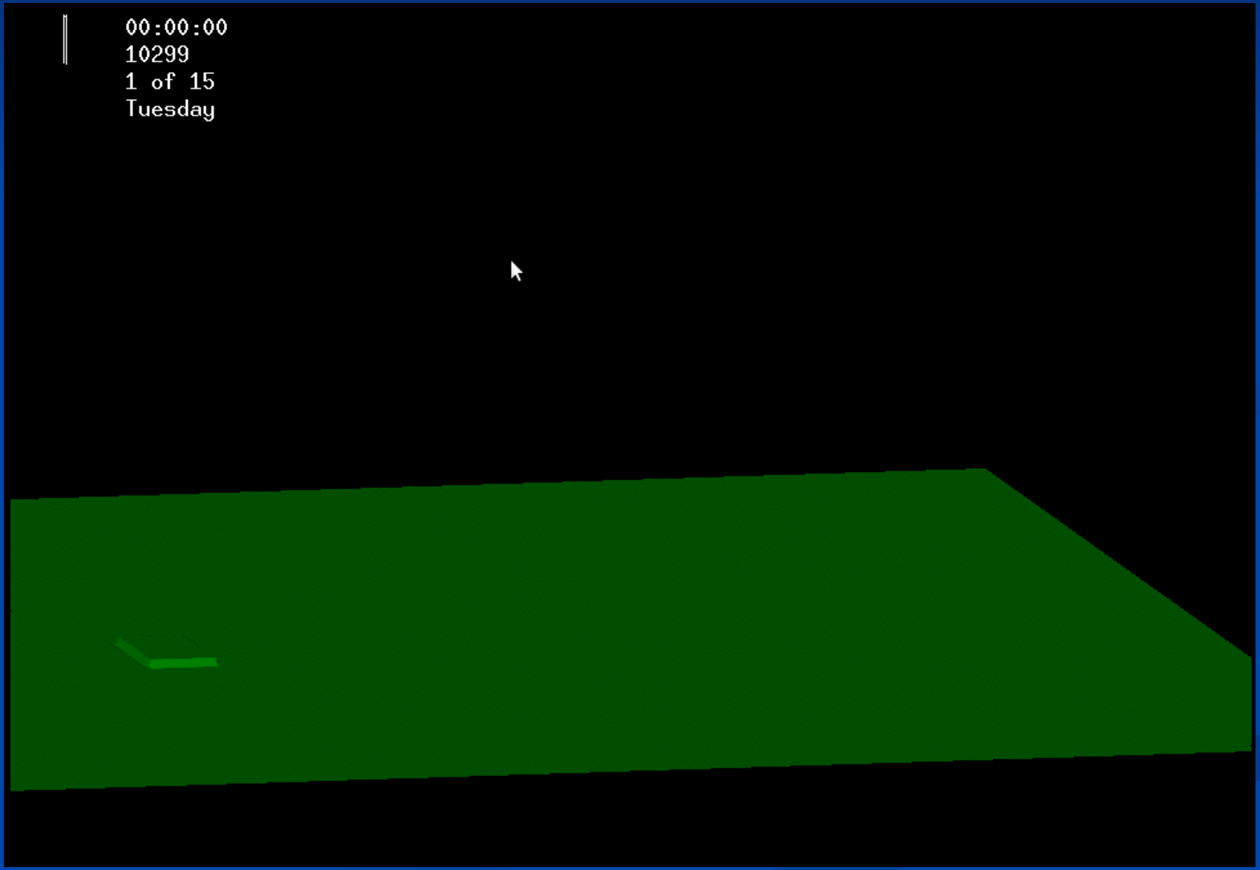
- EXP-BACKGROUND
  - Emulate regime of supercell dust ingestion within an already dusty atmosphere (i.e. SAL)
  - Initialized horizontally-homogeneous background dust profile
- EXP-STORM

  - Investigate dust ingestion purely by supercell itself
  - Initialized clean atmosphere with surface dust emission scheme active
- EXP-BOUNDARY



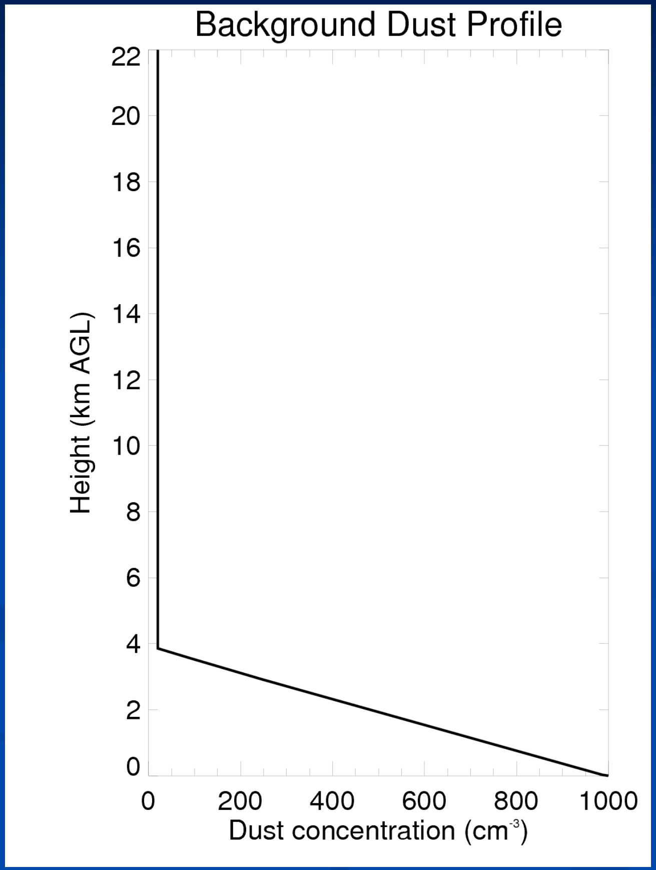
Supercell Initiation

- Warm bubble initiation
- Splits ~45 minutes
- Right mover main focus



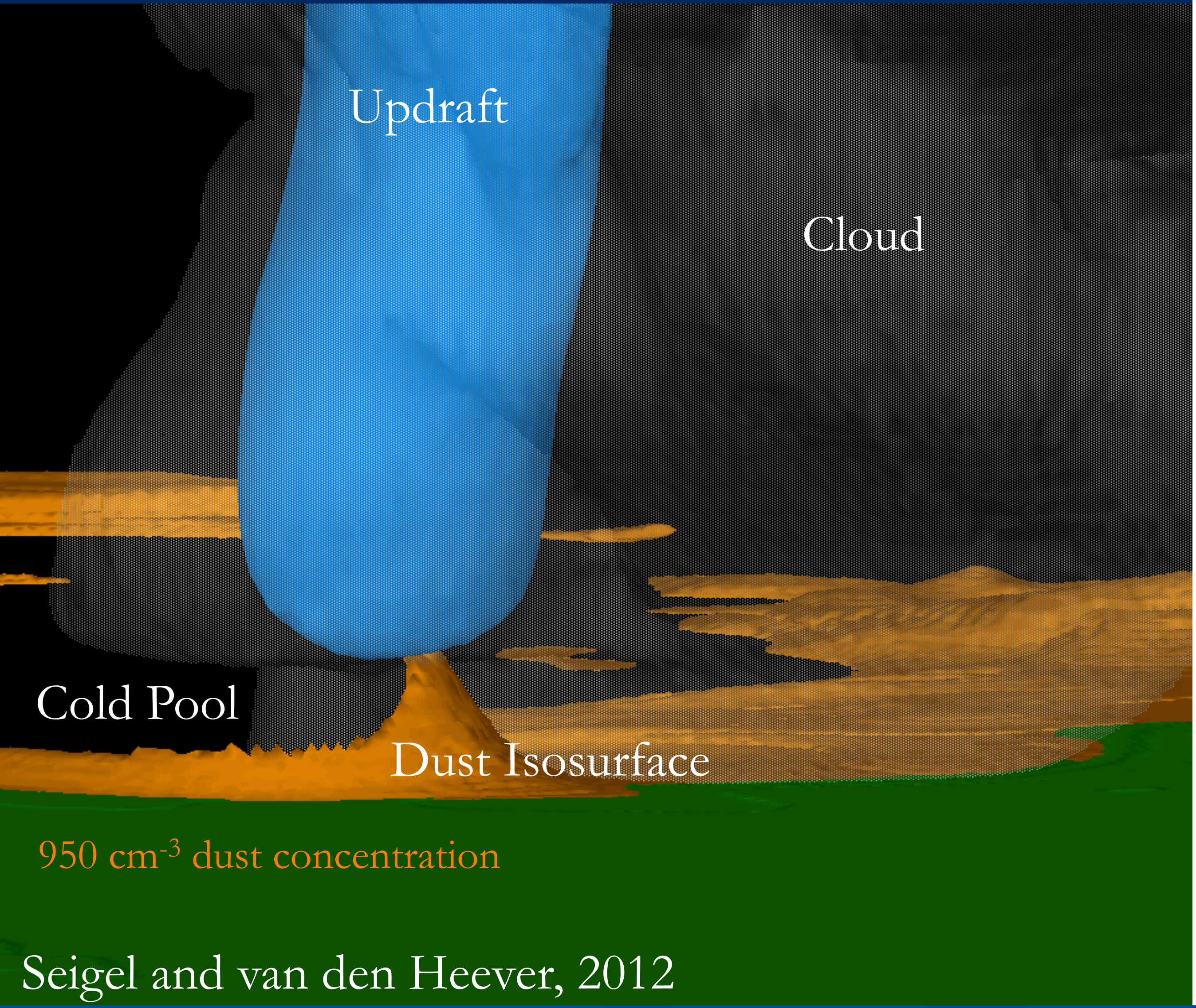
EXP-BACKGROUND

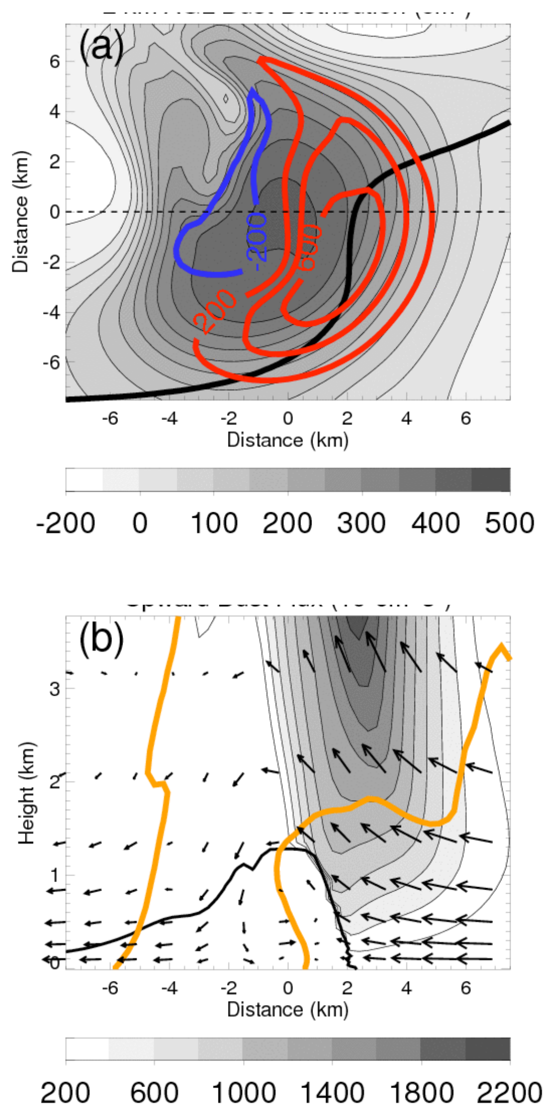
- Investigating dust ingestion by supercell within an already dusty environment
- Initialized with background dust
- Surface emission turned off



How do these towers ingest environmental dust?

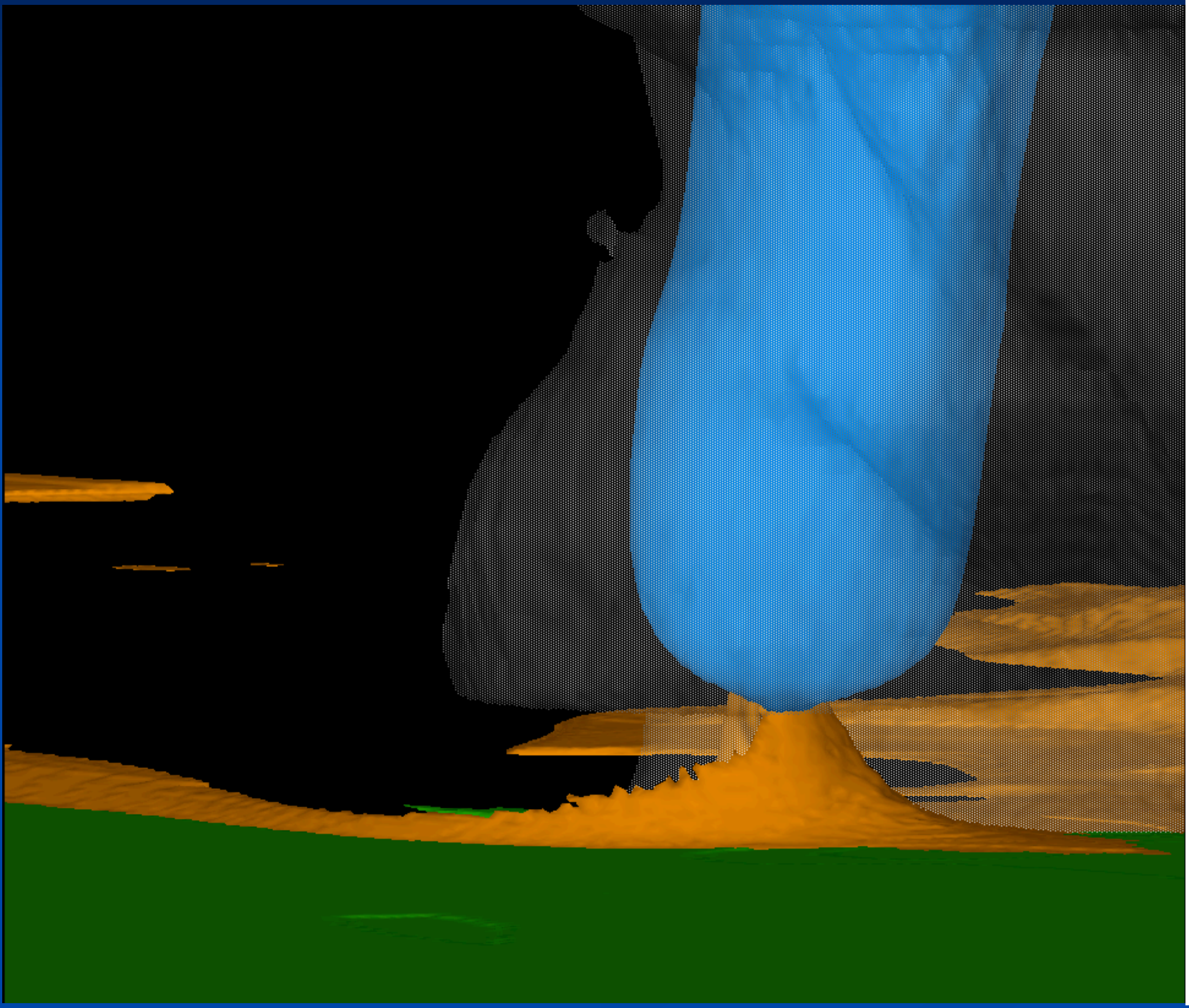
EXP-BACKGROUND

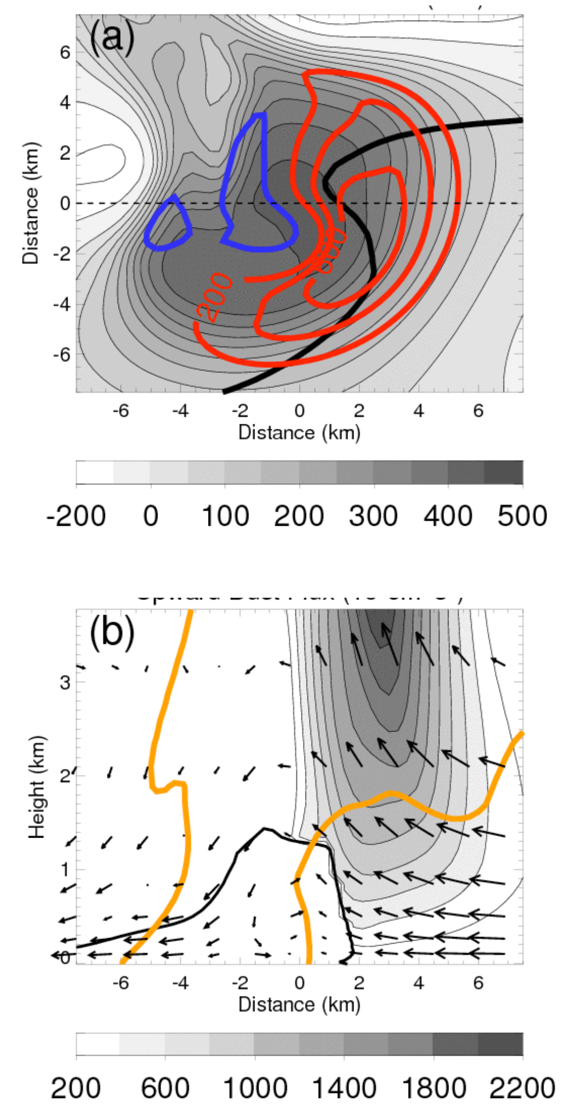




Seigel and van den Heever, 2012

EXP-BACKGROUND



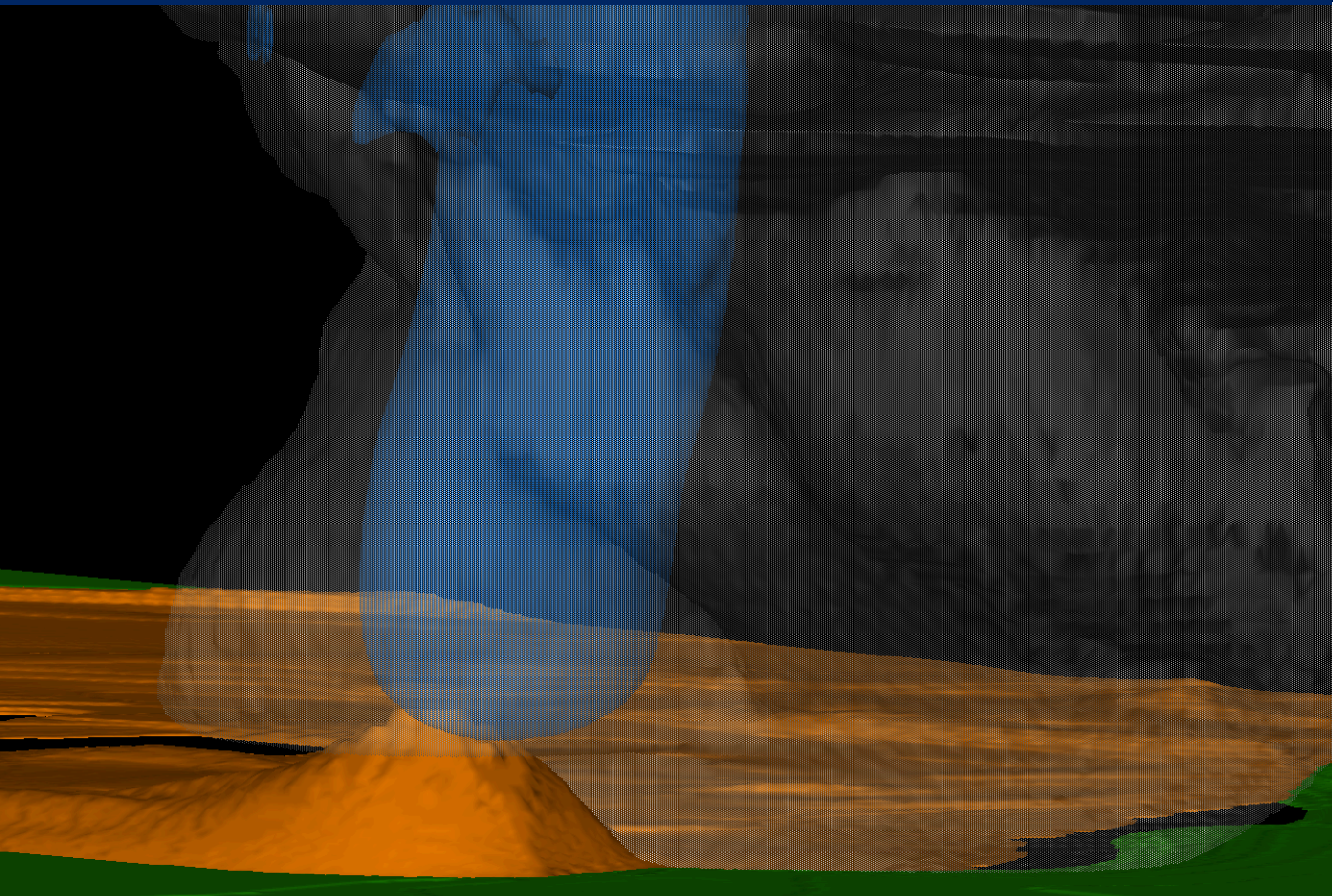


EXP-STORM

- Investigating ingestion purely by mechanics of supercell itself
- Initially **<u>clean</u>** environment
- Surface emission **<u>on</u>**

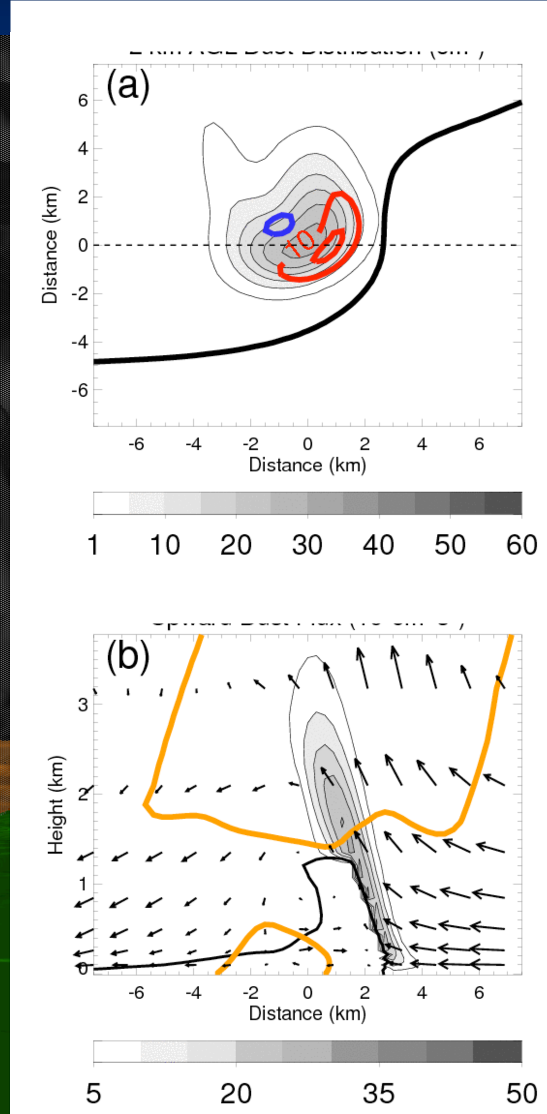
Does this lofted dust become ingested?

EXP-STORM

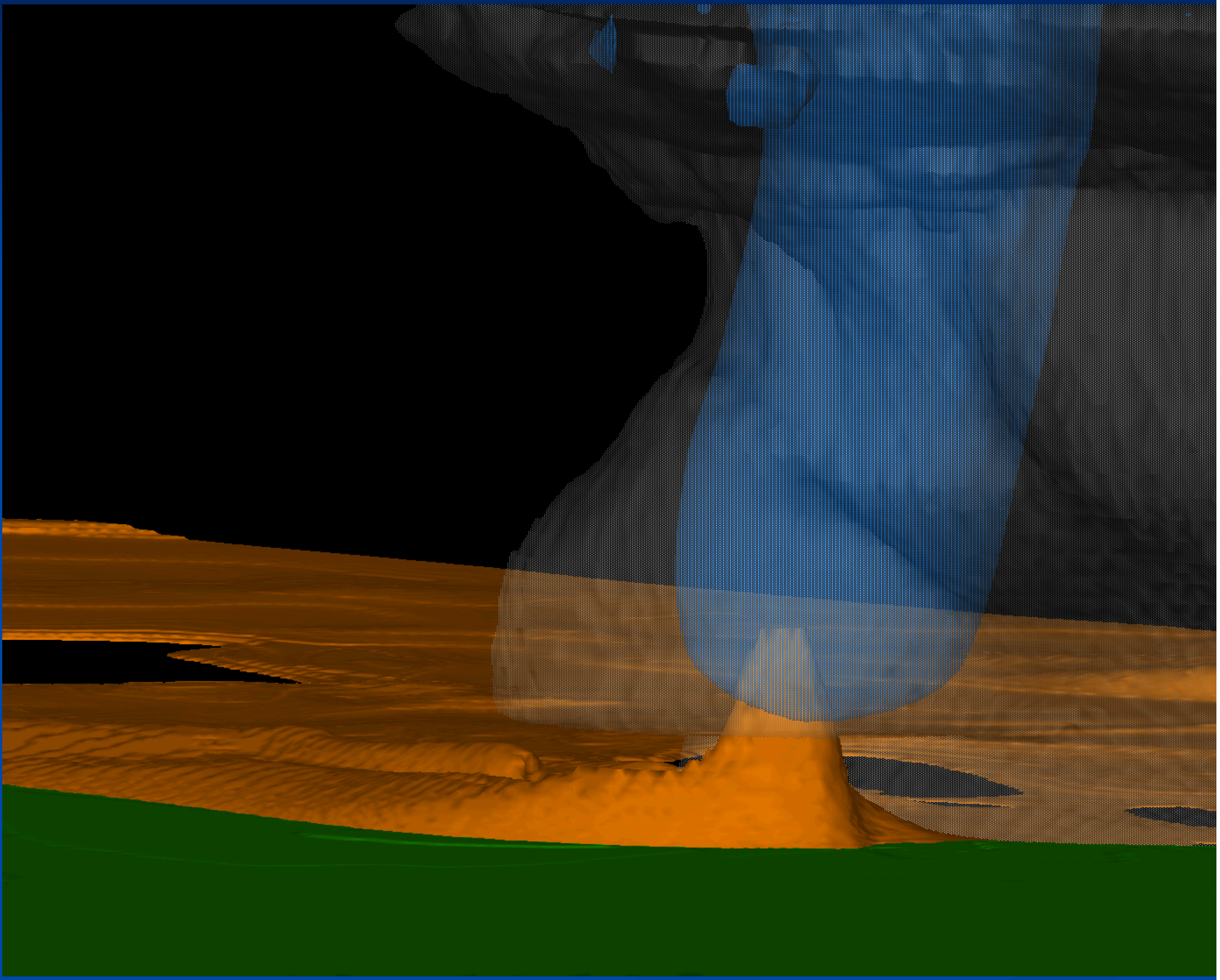


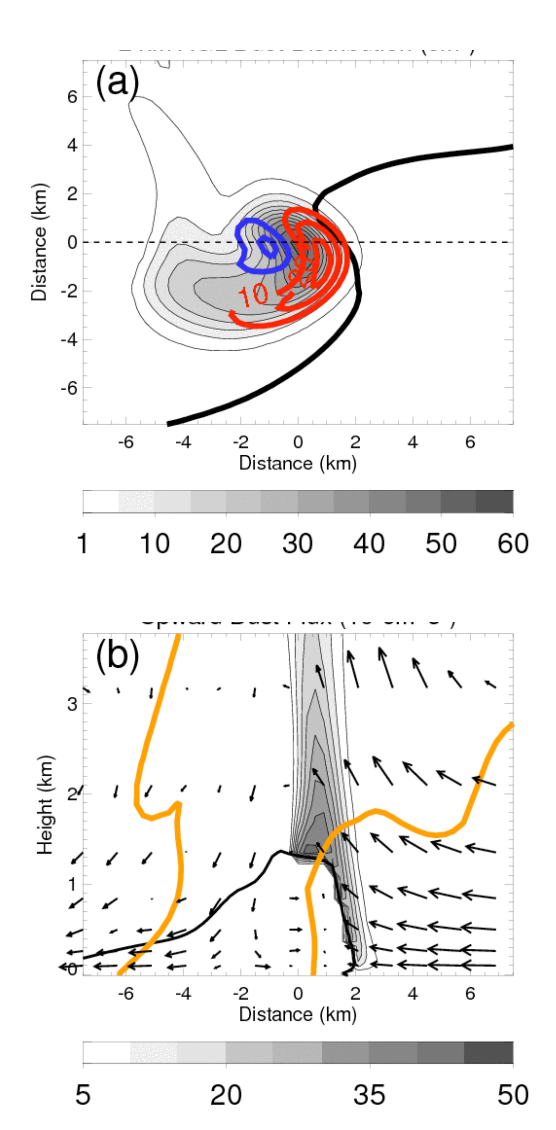
40 cm^{-3} dust concentration

Maximum dust concentrations in cold pool ~ 700-1700 cm^{-3}



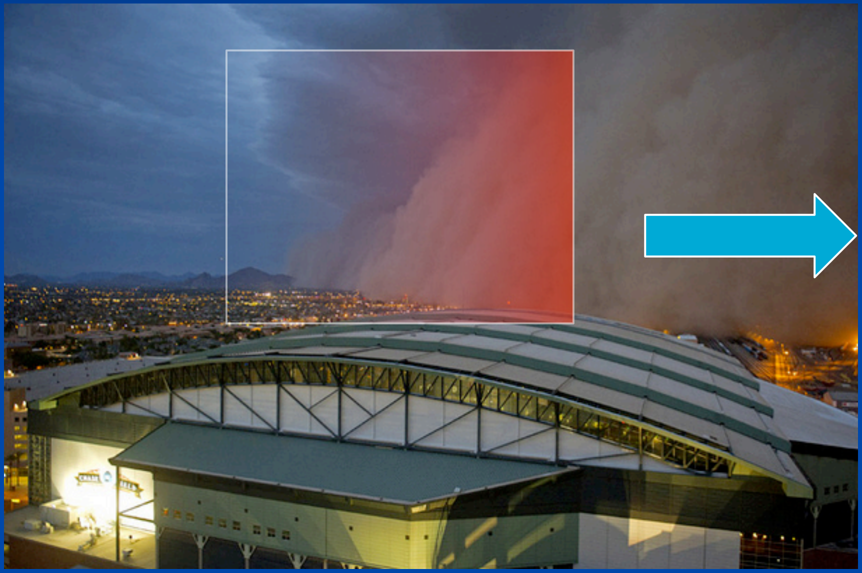
EXP-STORM

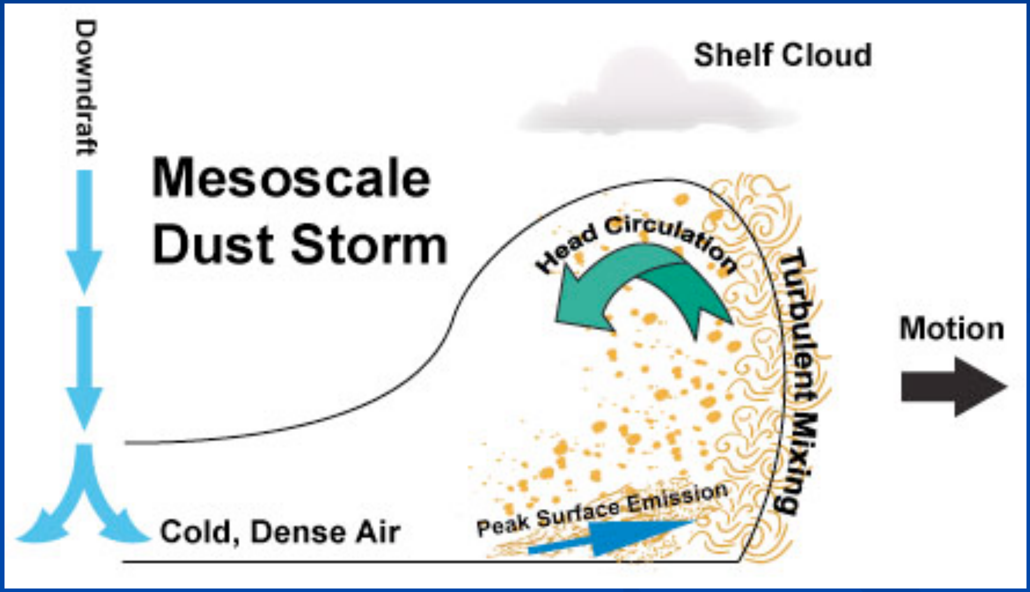



(a)
Distance (km)
Distance (km)
10
1 10 20 30 40 50 60
(b)
Height (km)
Distance (km)
5 20 35 50

EXP-STORM

Cold pool lofting and storm ingestion mechanism

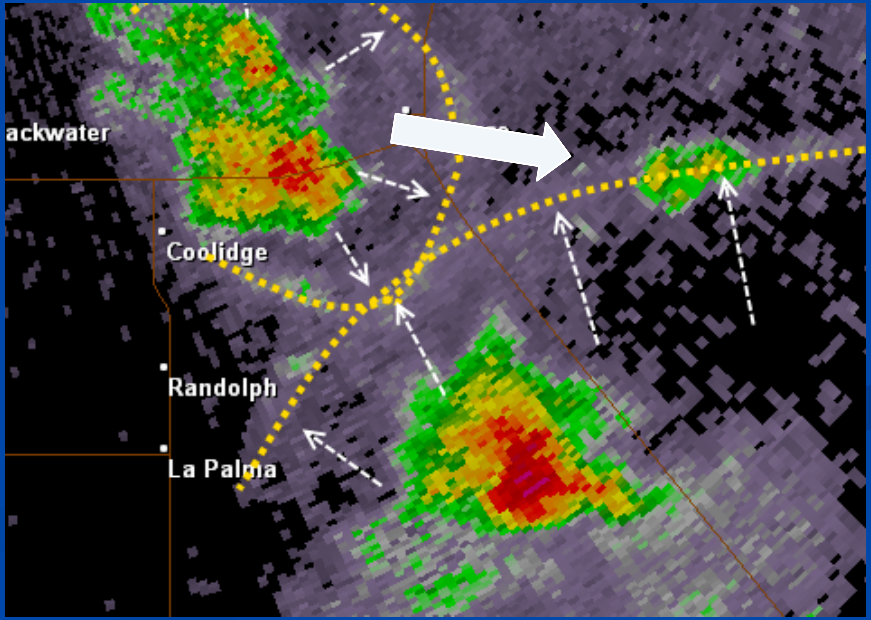




Seigel and van den Heever, JAS, 2012

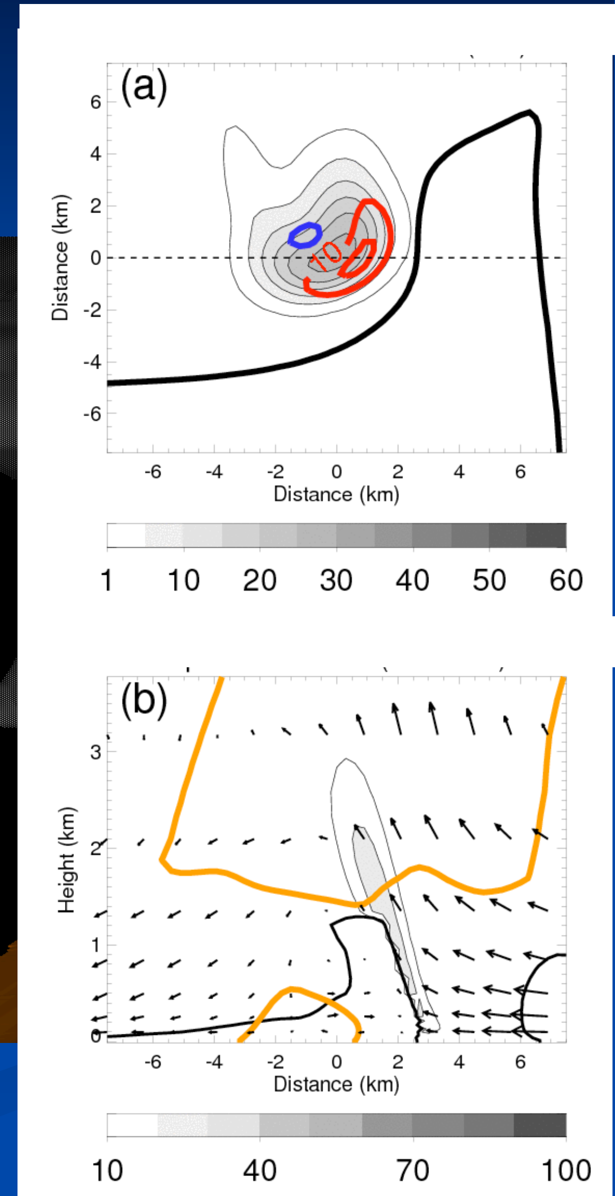
EXP-BOUNDARY

- Investigating ingestion within complex regime of boundary interactions
- Initially **clean** environment
- Surface emission **on**
- Convergence boundary initialized with -5 K cold pool ahead of supercell

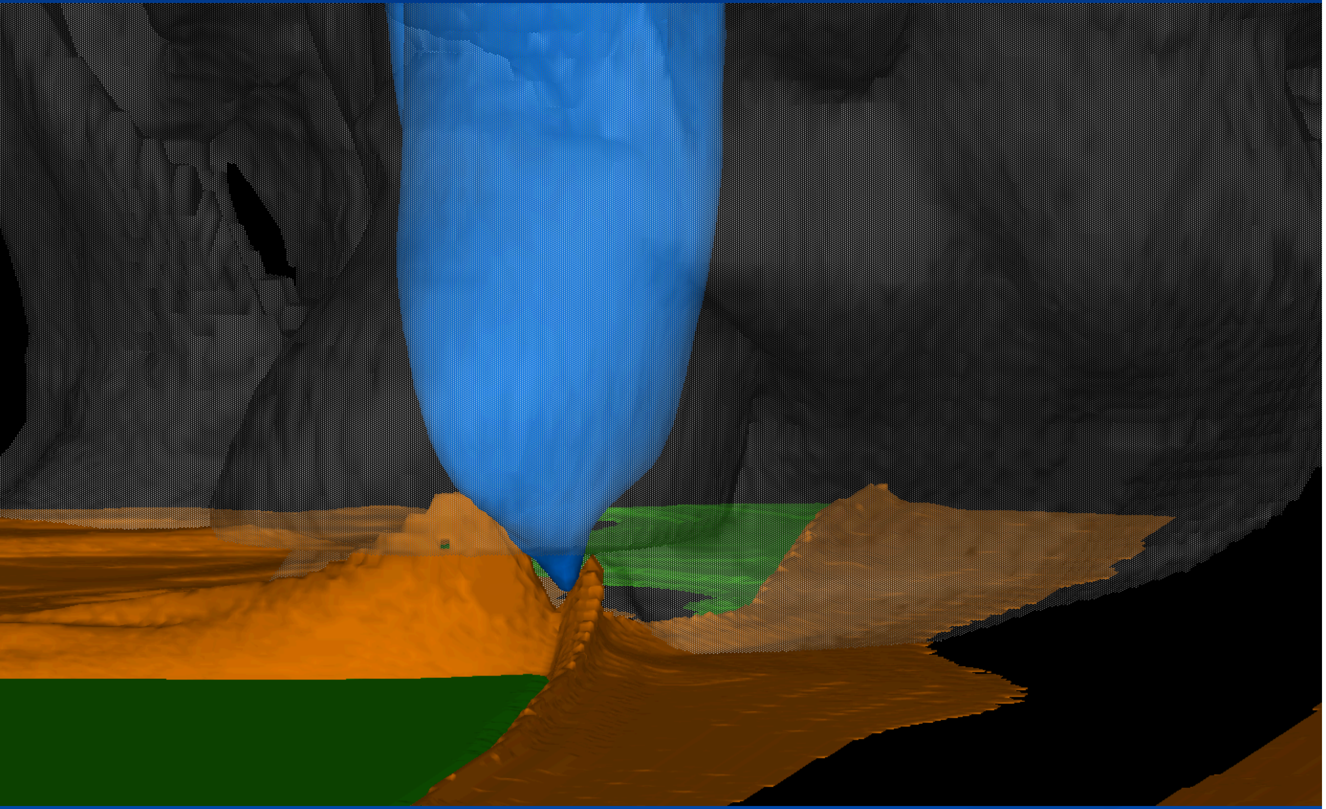


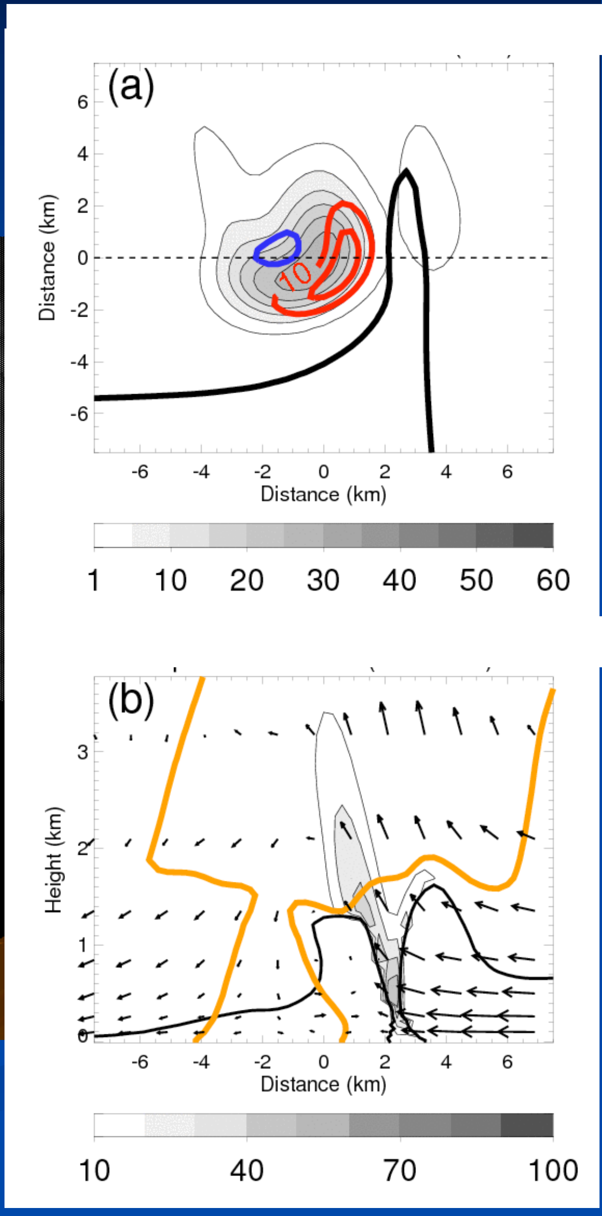
How does ingestion change as this dust storm near the developing cell?

EXP-BOUNDARY

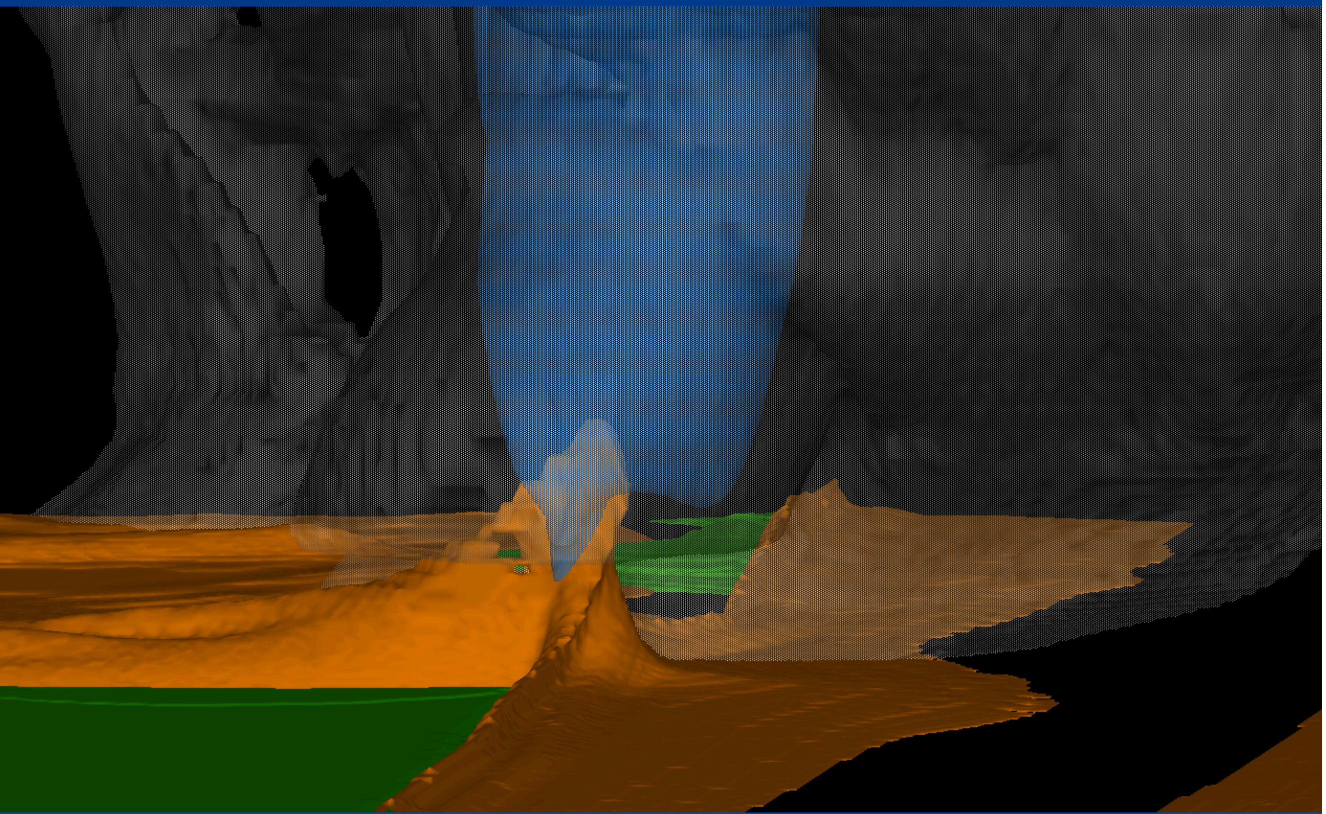


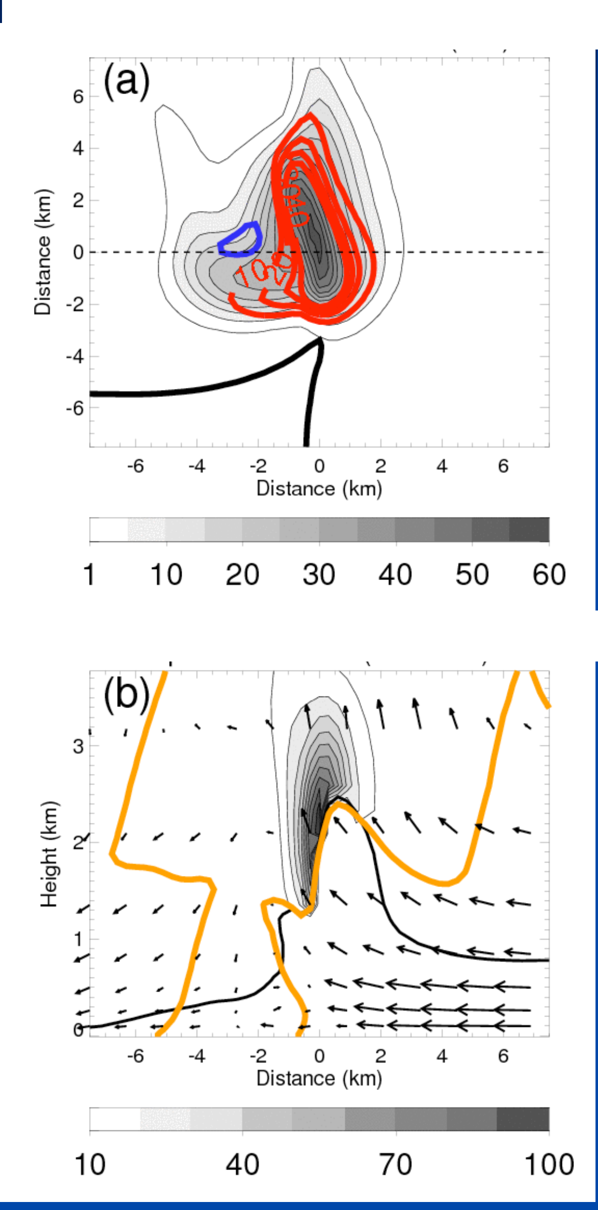
EXP-BOUNDARY





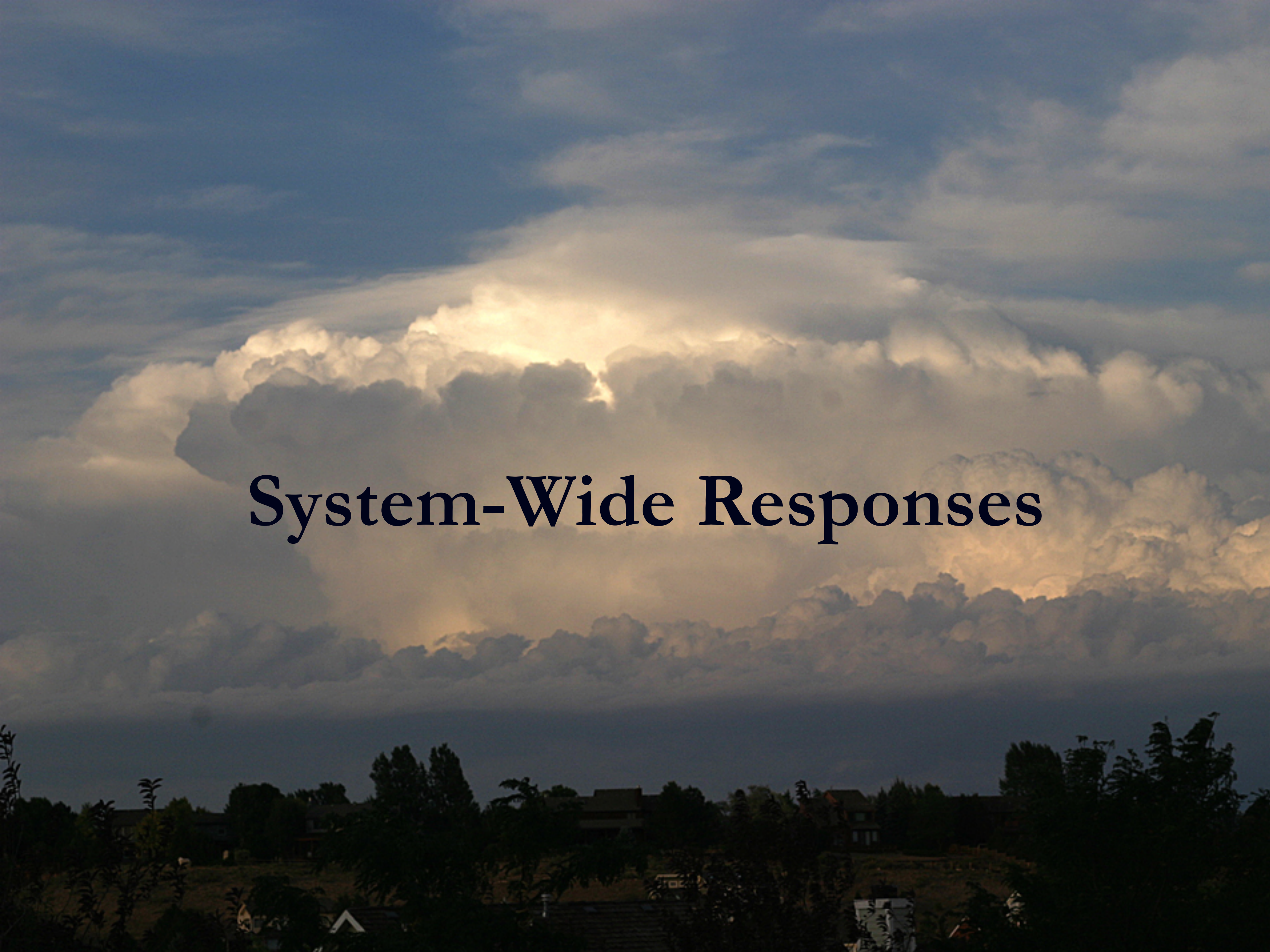
EXP-BOUNDARY





Dust Ingestion Summary

- Dust concentrations ingested in the updraft are at least an order of magnitude greater in the background case than in the cold pool generated case
- It is extremely difficult to ingest dust into the parent storm when relying solely on the action of the storm itself
- Microphysical-dynamical interactions may therefore be background-aerosol limited


System-Wide Responses

Trimodal Distribution (Johnson et al 1999)

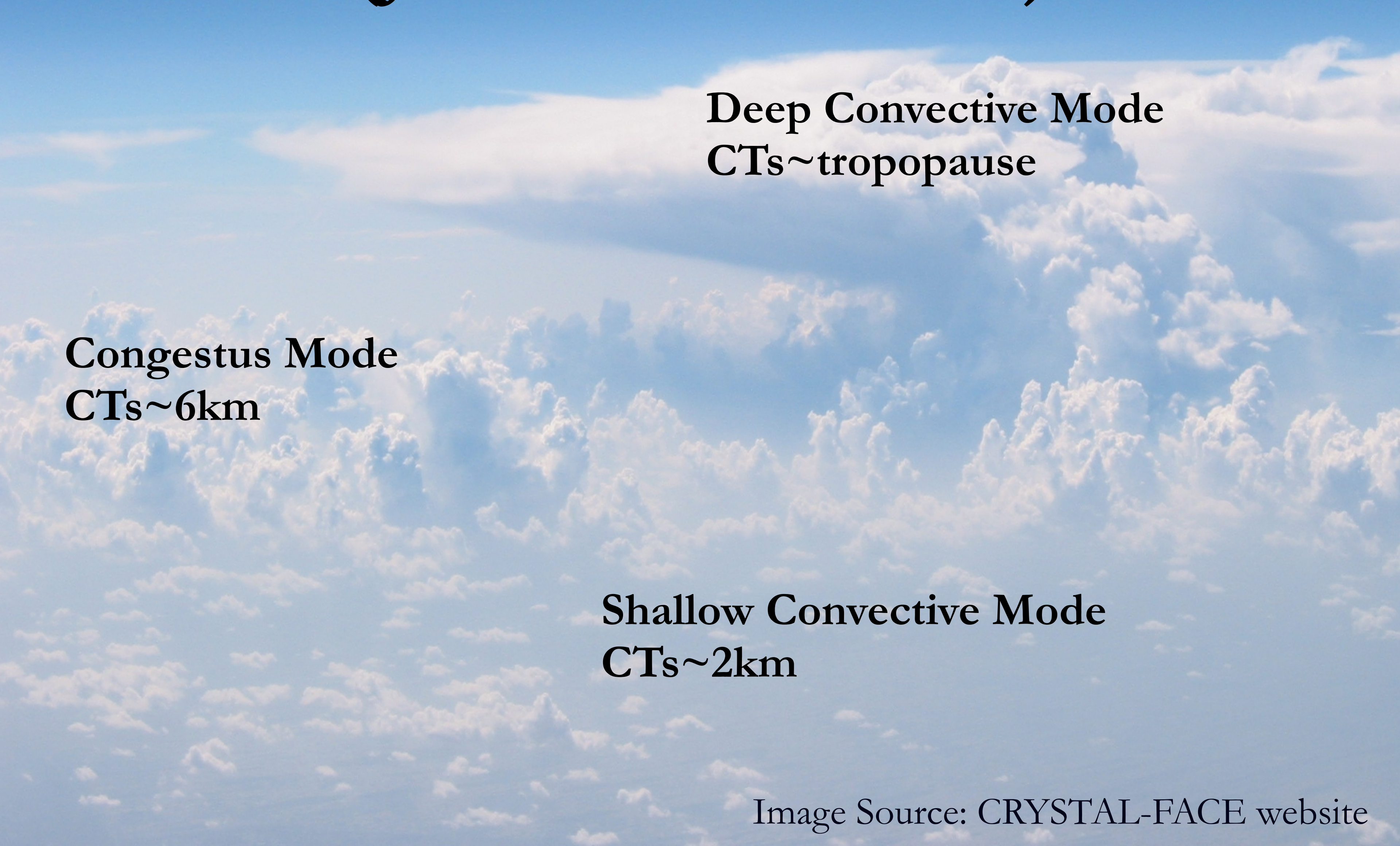
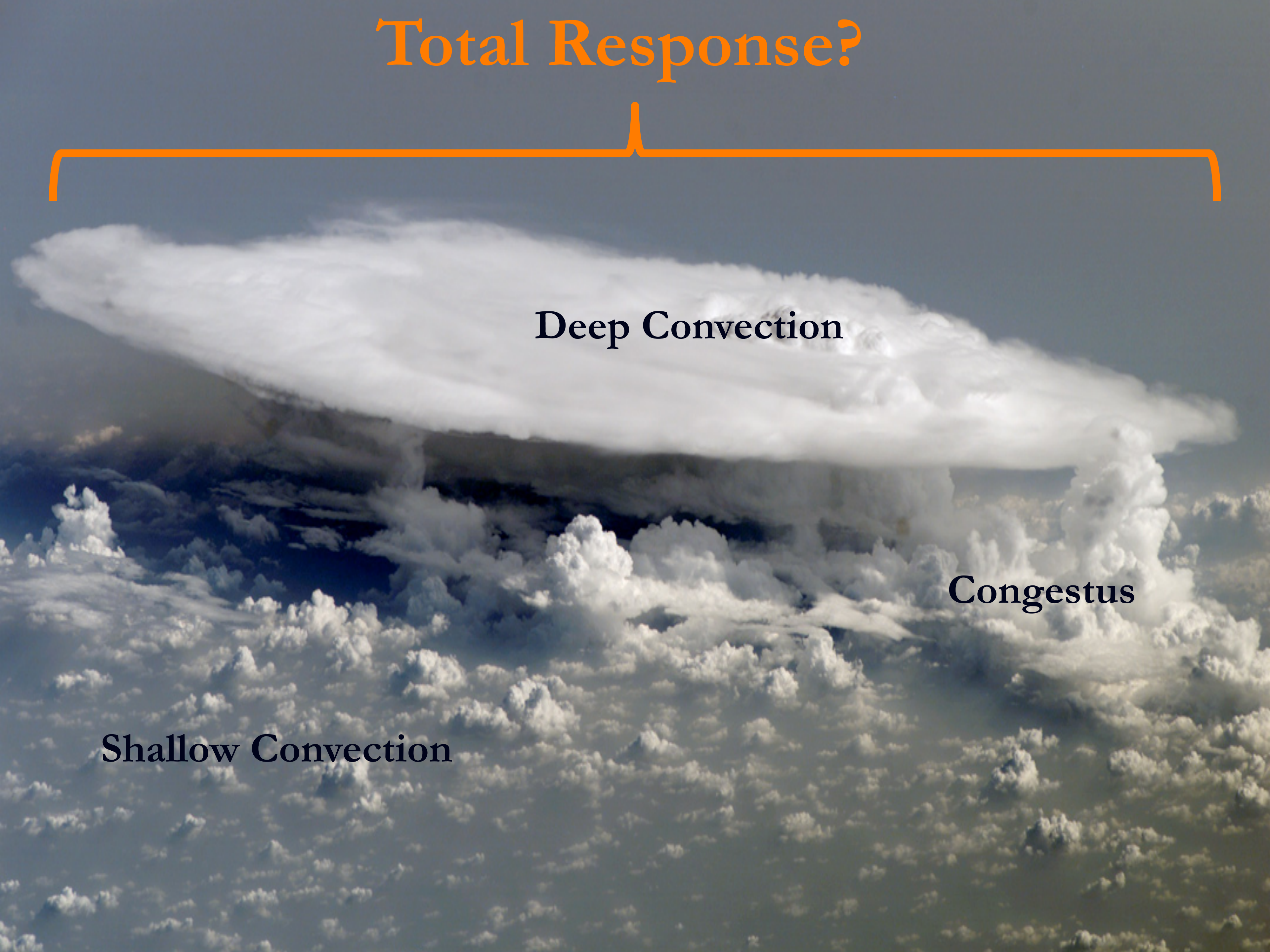


Image Source: CRYSTAL-FACE website


Total Response?
Deep Convection
Congestus
Shallow Convection

Goal

- To investigate the response of tropical convective systems to aerosol indirect forcing from a local AND system-wide perspective
- To be achieved through the use of CRM simulations under a Radiative Convective Equilibrium (RCE) framework
- Tropical atmosphere is never far from RCE => suitable framework to study convective, microphysical and radiative effects of tropical

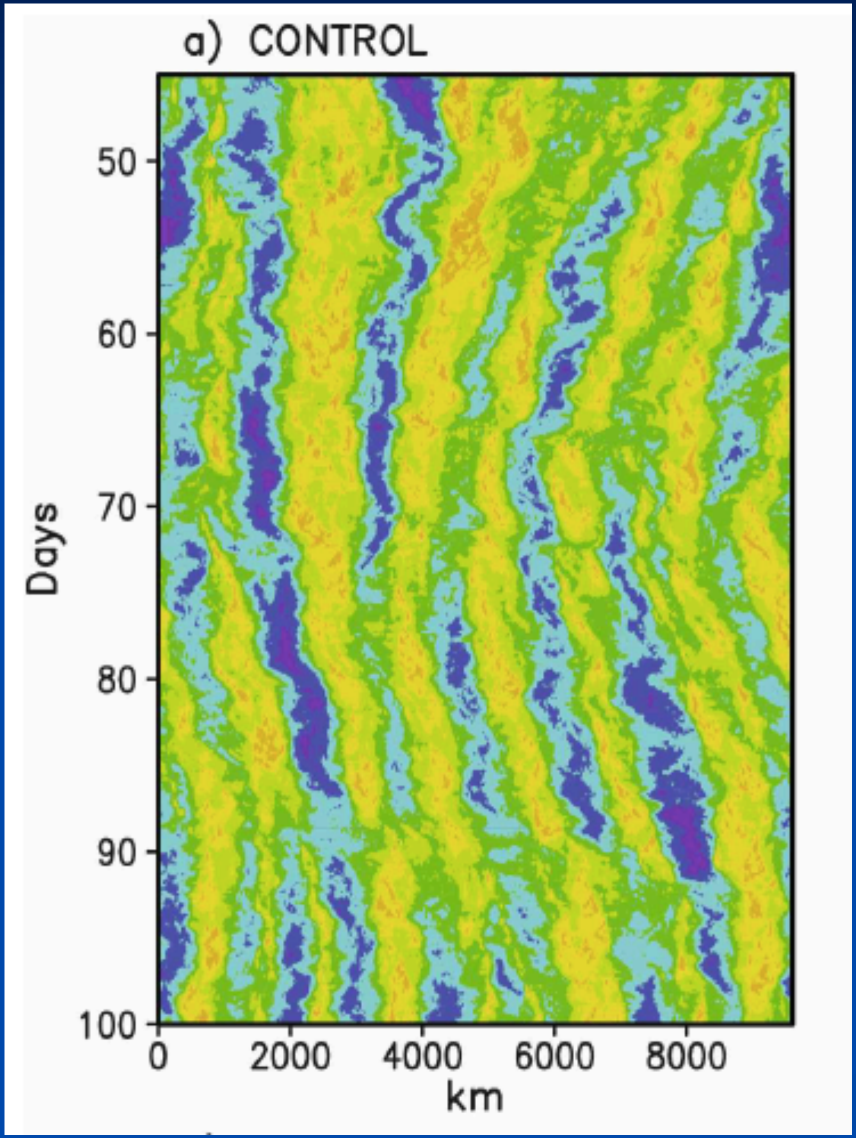
Model Setup

- 2D and 3D model grid
  - 500m to 1 km grid spacing
  - 10,000 km in zonal direction
  - Variable grid spacing in the vertical
- Time period: 100 days
- Periodic lateral boundary conditions
- Oceanic boundary with fixed SST (300K)
- Constant solar zenith angle
- Harrington 2-stream radiation scheme
- TOGA-COARE sounding with zero mean wind
- Convection - randomized perturbations to potential temperature

Experiment Setup

- Control Run
  - allow CONTROL simulation to reach RCE (60 days)
  - introduce aerosol layer between 2 and 4 km AGL => Saharan dust layer over the Atlantic Ocean
  - aerosol layer updated each time step
  - run simulations for another 40 days
- CCN Experiments:
  - Experiments: 100, 200, 400, 800, 1600 cc^{-1}

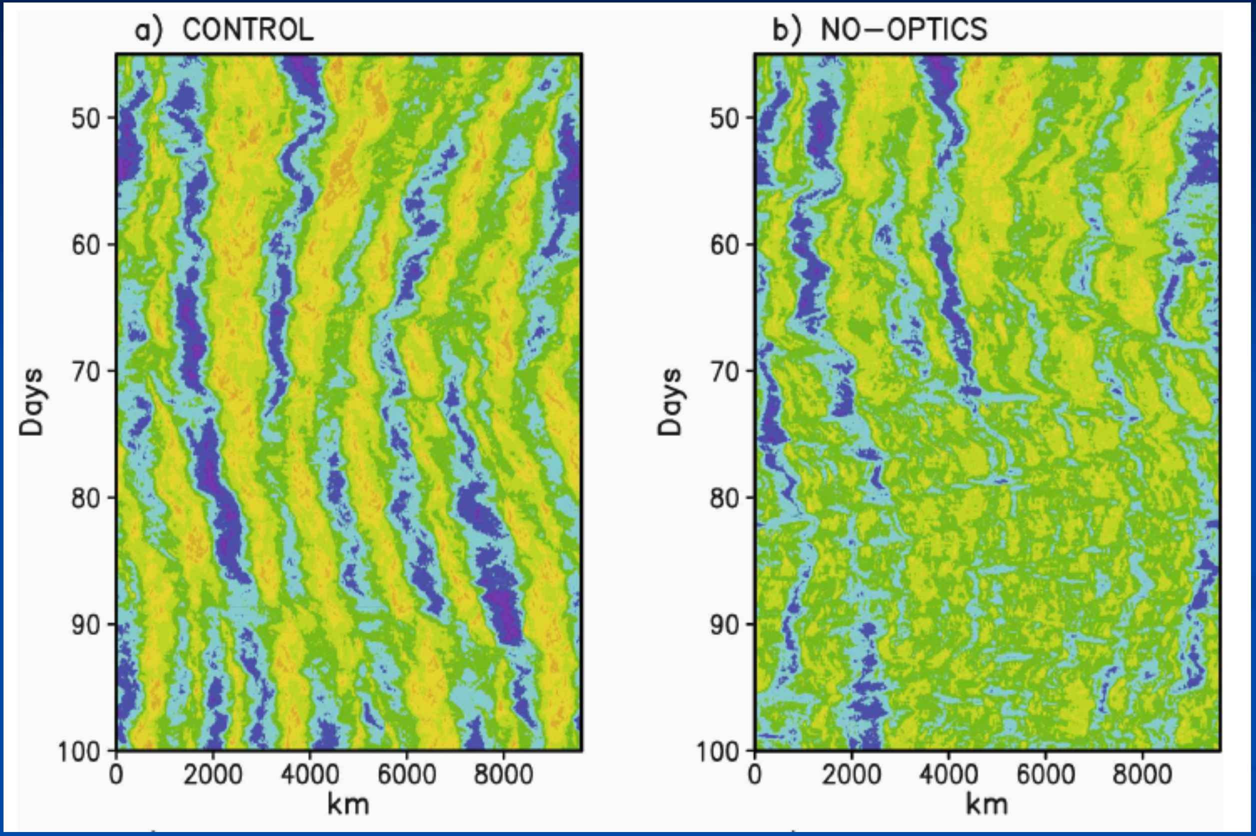
Convective Organization



- Self-sustaining moist and dry bands
- 3D experiments

Time series of precipitable water (mm) for fully interactive radiation scheme (left) and interactive radiation without contributions by clouds and precipitation (after Stephens, van den Heever and Pakula, 2008)

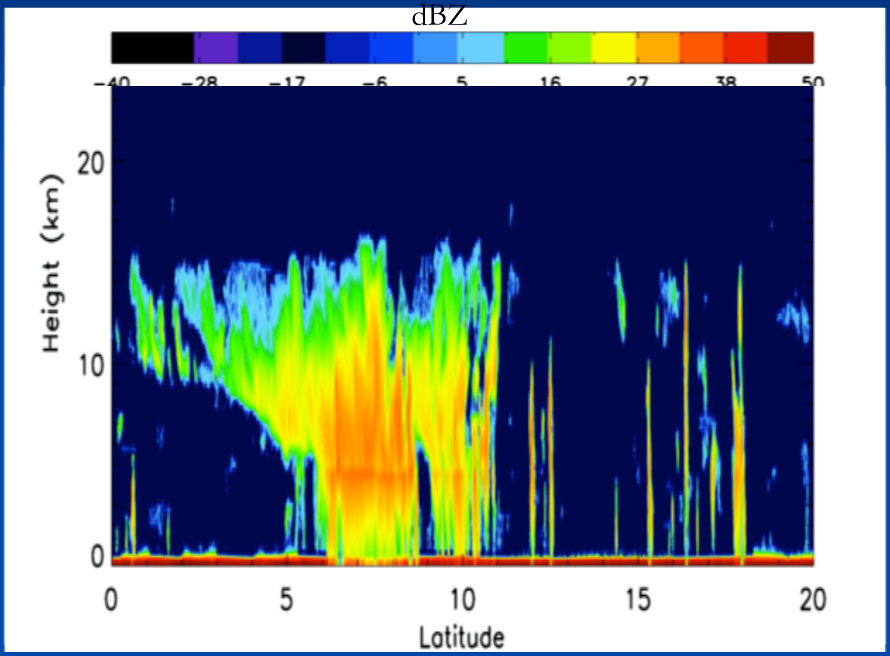
Radiative Influences

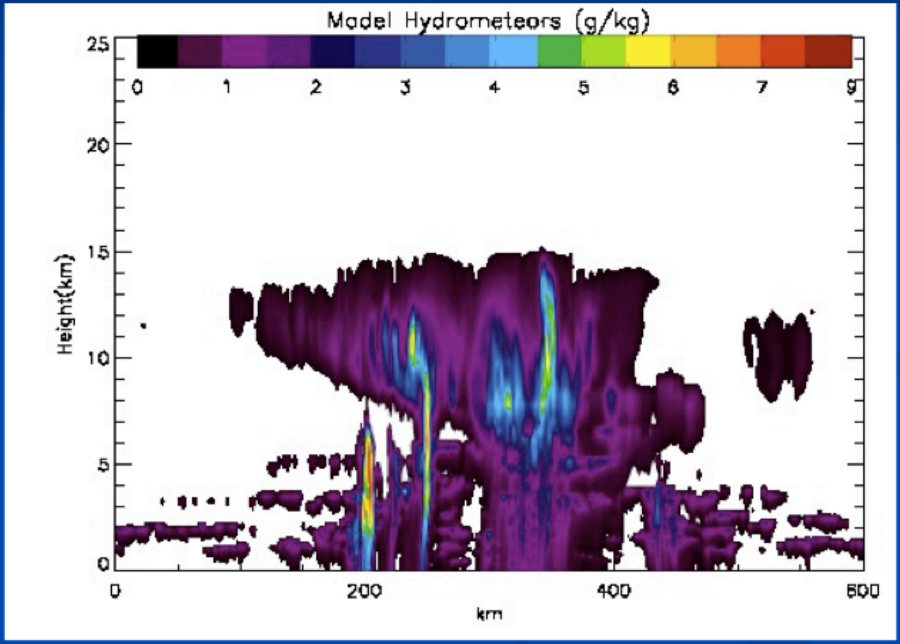


Time series of precipitable water (mm) for fully interactive radiation scheme (left) and interactive radiation without contributions by clouds and precipitation (after Stephens, van den Heever and Pakula, 2008)

- Breakdown of banded organization
- Effects of clouds on radiative heating and feedbacks to convective organization important

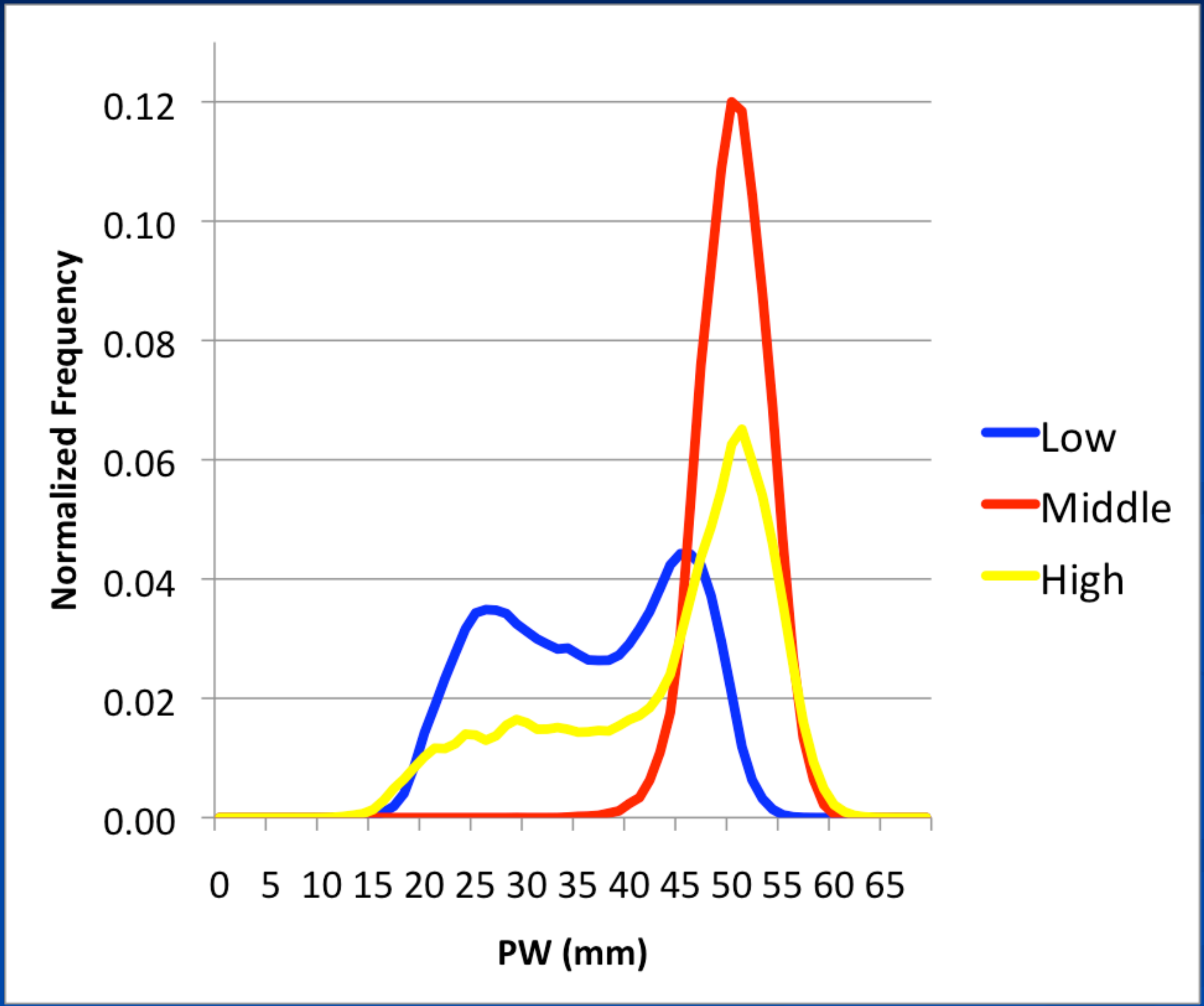
Trimodal Distribution





Trimodal structure typical of tropical convection (Johnson et al., 1999) is evident in CloudSat data (left) and RAMS output (right)

PW and Cloud Regime



Low: CTs < 4km
Middle: 4 - 7 km
High: CTs > 7km

Normalized frequency of cloud regime as a function of PW for the CCN-100 case

PW Budget

$$\frac{\partial}{\partial t}$$

Local rate of change in PW (mm/hr)

Evaporation and Precipitation rates (mm/hr)

Horizontal water vapor flux convergence (mm/hr)

Equation contains no forcing information

PW Budget Terms

Moistening by evaporation

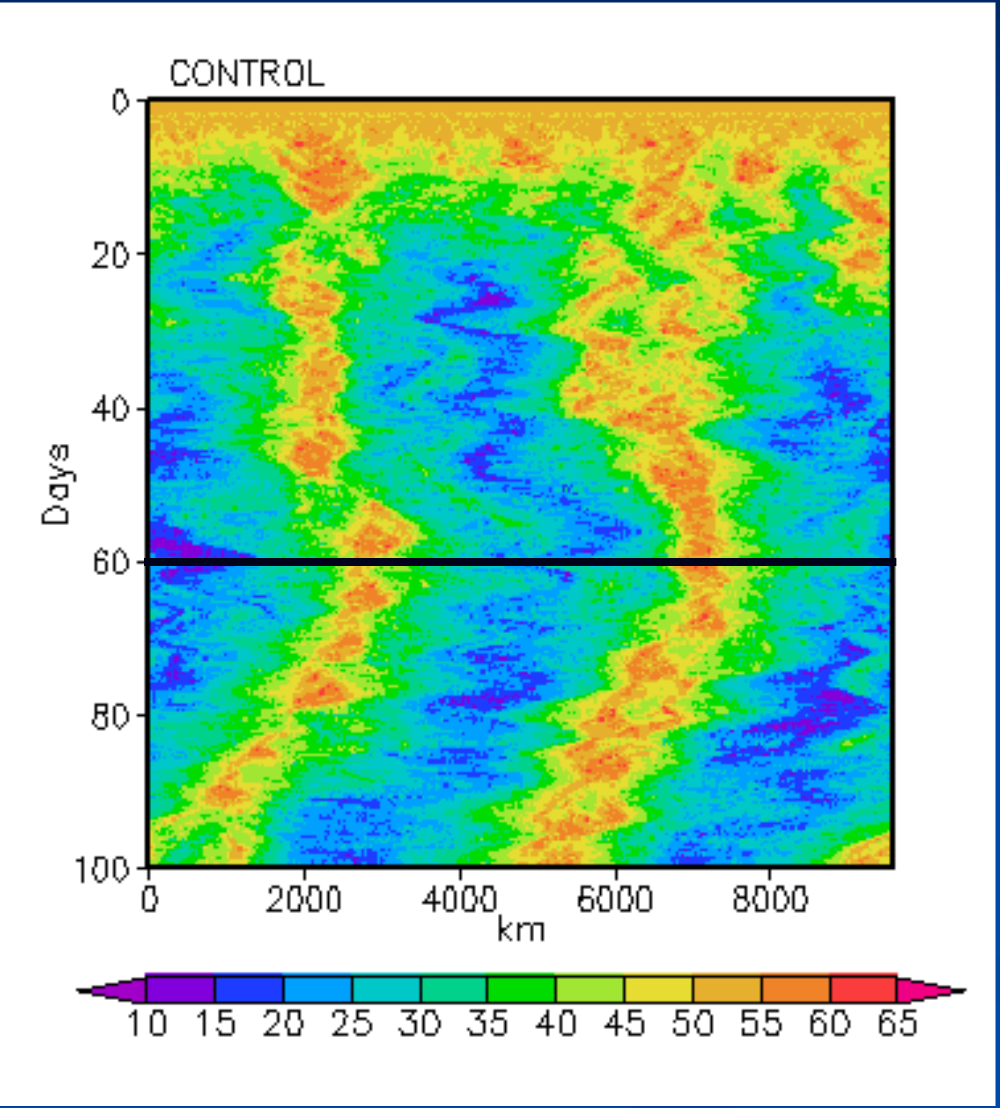
Moistening by convergence

Drying through divergence

Drying through precipitation – prevents run away moistening

Moderate zones => evaporation balanced by precipitation and divergence

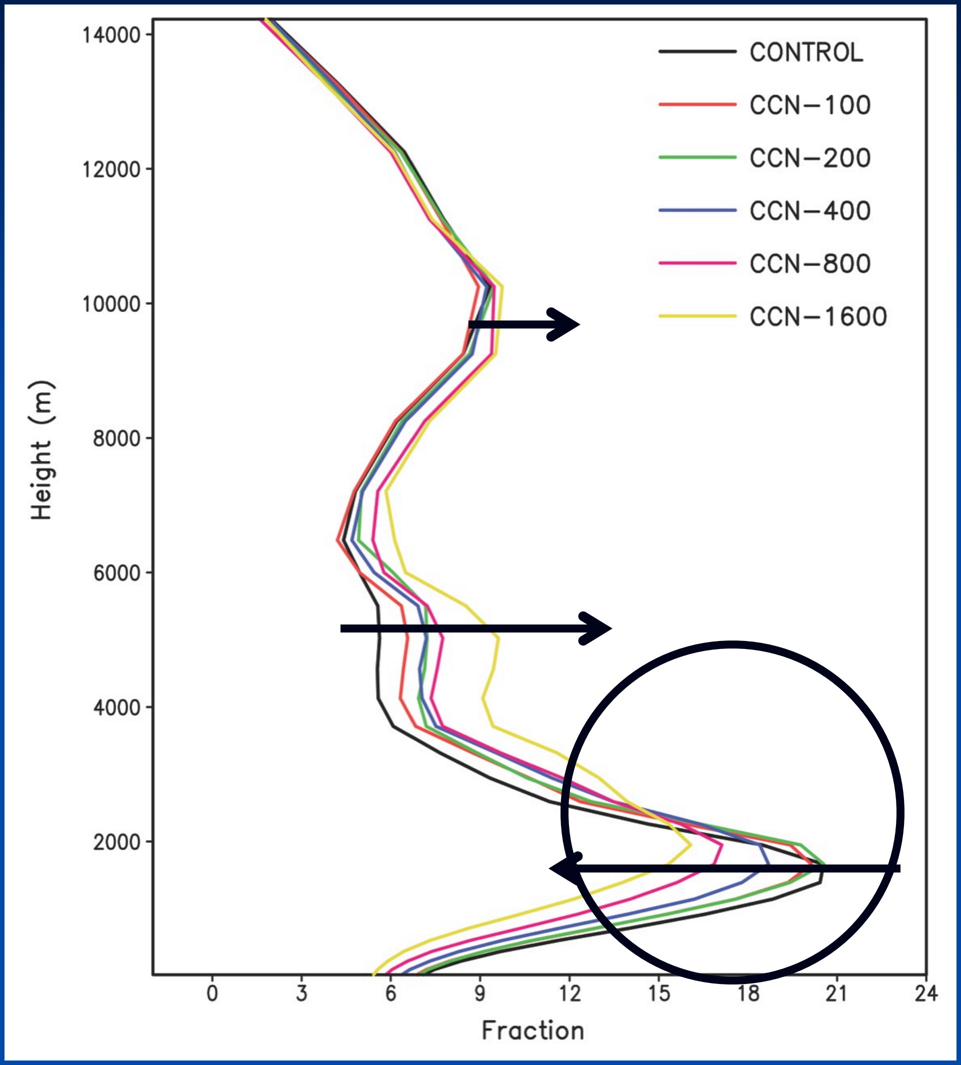
Aerosol Experiments



- Self-sustaining moist and dry bands
- Aerosol experiments started at day 60
- 2D

Hovmuller plot of vertically-integrated water vapor (mm) for the Control experiment

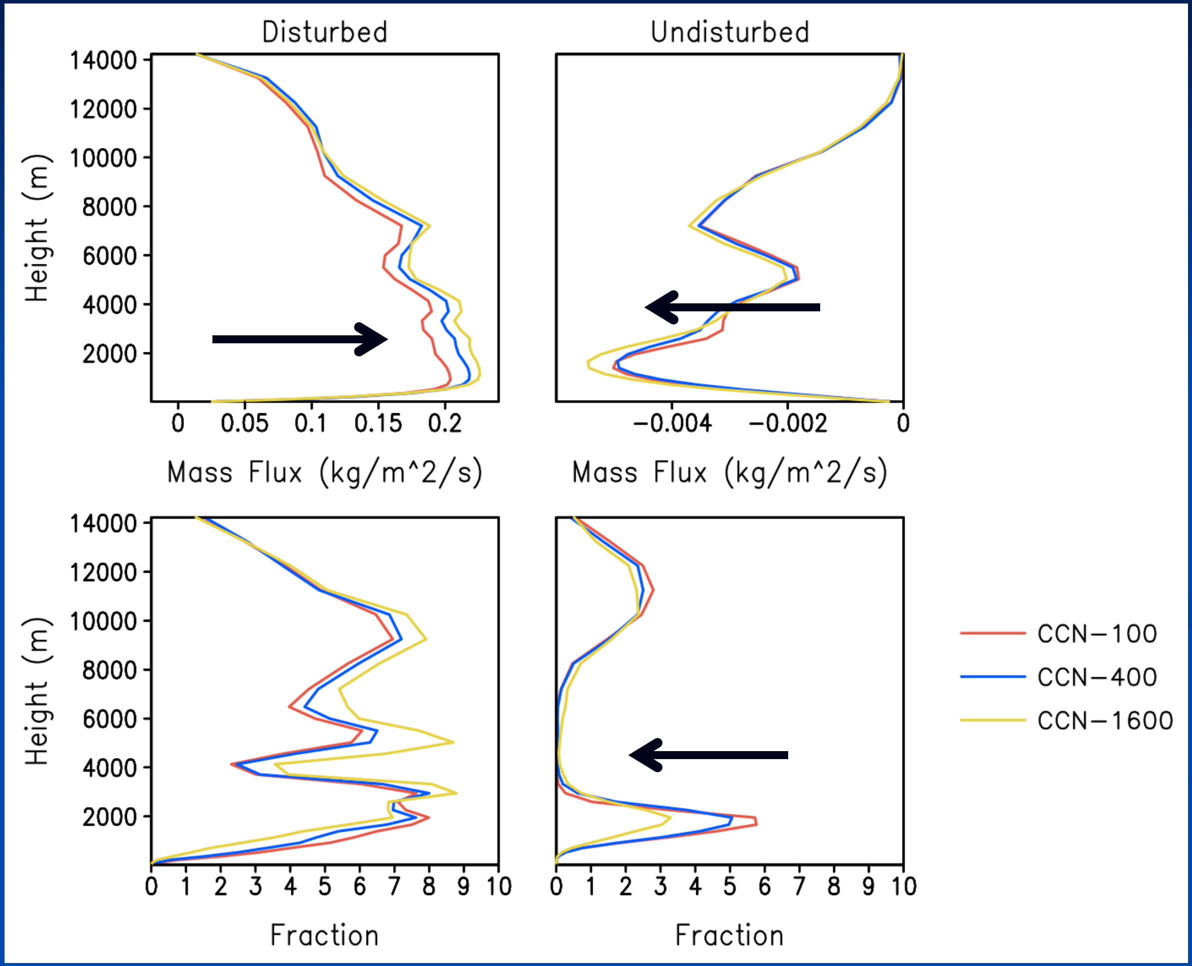
Aerosol Impacts on Trimodal Dist



Vertical profiles of temporally (40 days) and spatially-averaged total condensate

- Enhanced aerosol concentrations:
  - Reduced shallow cloud fraction
  - Enhanced congestus fraction
  - Enhanced deep convective mode fraction

Large Scale Effects on Shallow Mode

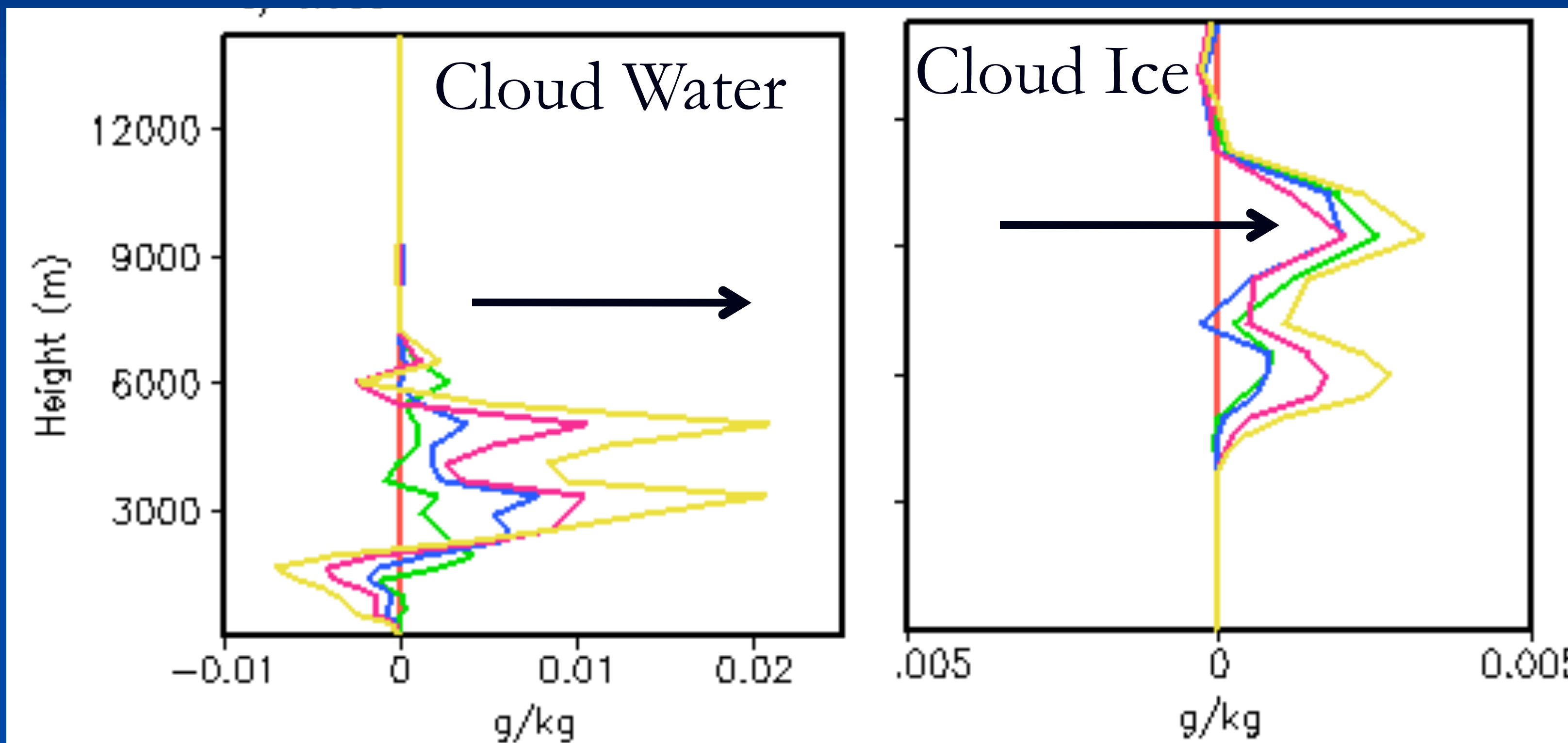


- Higher CCN concentration
  - Greater downward mass flux in undisturbed regions
  - Reduced shallow cloud fraction

Convective mass flux and cloud fraction for the disturbed and undisturbed regions as a function of aerosol concentrations

Liquid Water and Ice Response

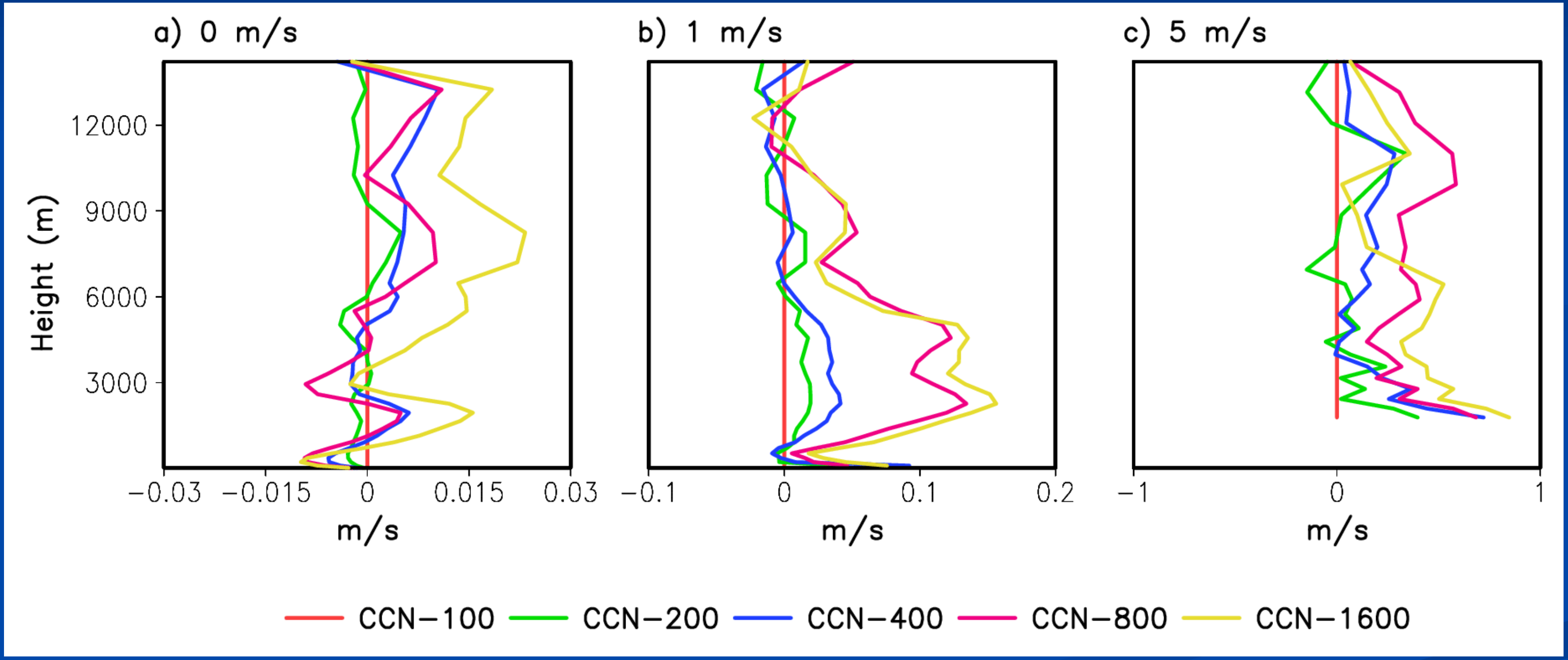
- Enhanced aerosol concentrations => greater cloud water and cloud ice



Vertical profiles of temporally and spatially-averaged cloud water and cloud ice represented as a difference from the Control experiment

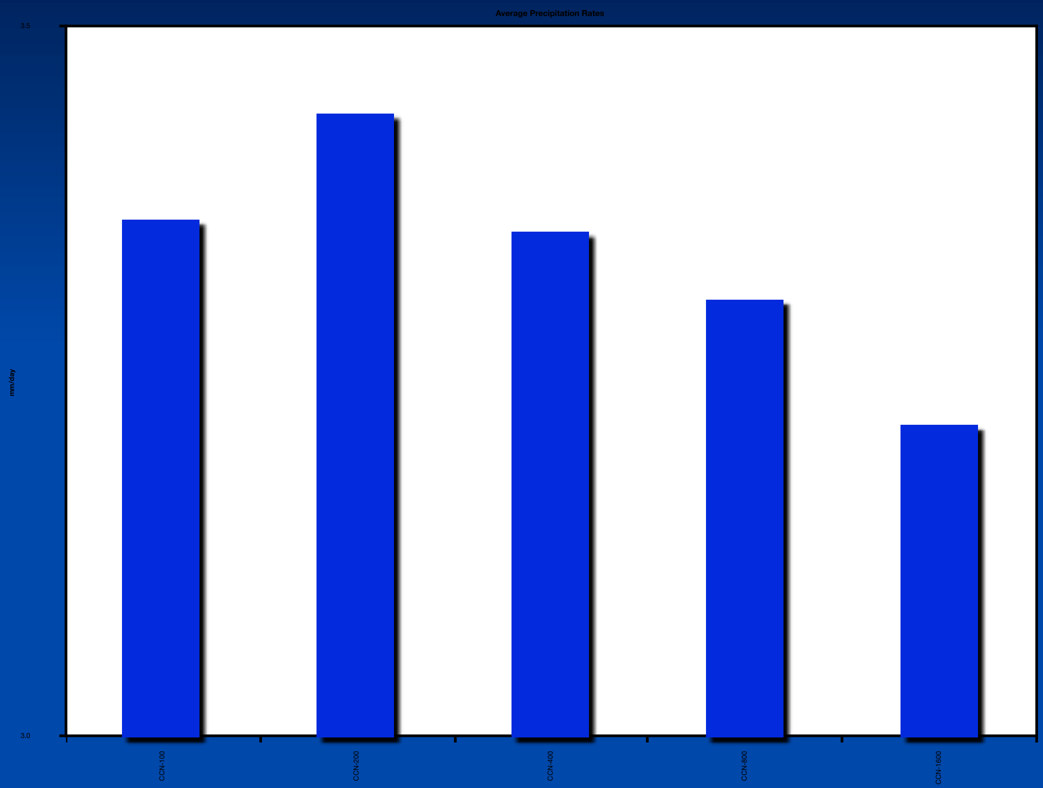
Dynamic Response

- Enhanced CCN concentrations => stronger updrafts



Vertical profiles of temporally and spatially-averaged updraft strength represented as a difference from the Control experiment for various updraft thresholds

Domain-Wide Precipitation Rates



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

- Averages are comparable to those observed in the Tropics
- Enhanced CCN
  - decreased surface precipitation rates
  - in keeping with aerosol indirect theory (Twomey, 1974; Albrecht, 1989)

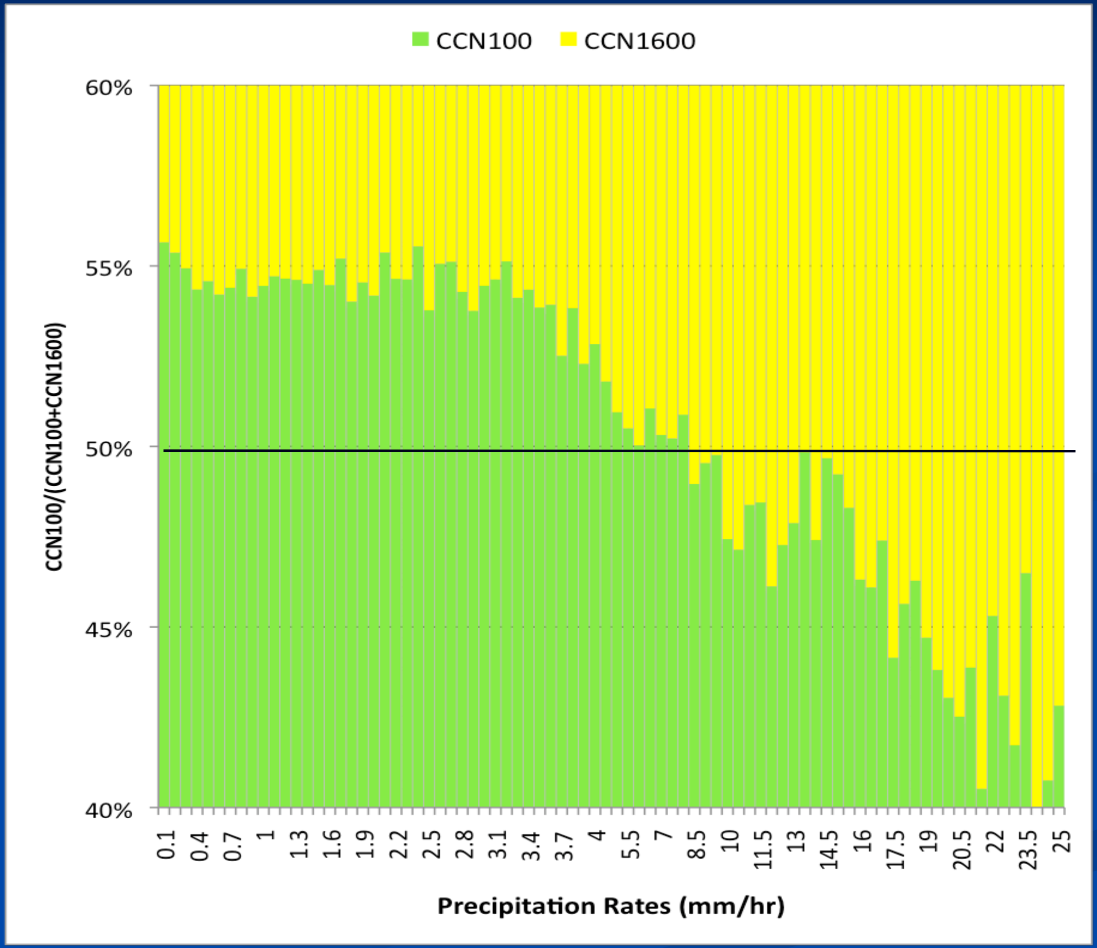
Precipitation Contribution (%)

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

Precipitation Rate Frequencies

Enhanced CCN concentrations

- reduced relative frequency of light rain points
- greater relative frequency of heavier rainfall points



Precipitation Summary

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

Deep Convective Mode
Enhanced precipitation

Aerosol indirect forcing may therefore have greatest effect on the frequency and intensity of precipitation compared with overall totals

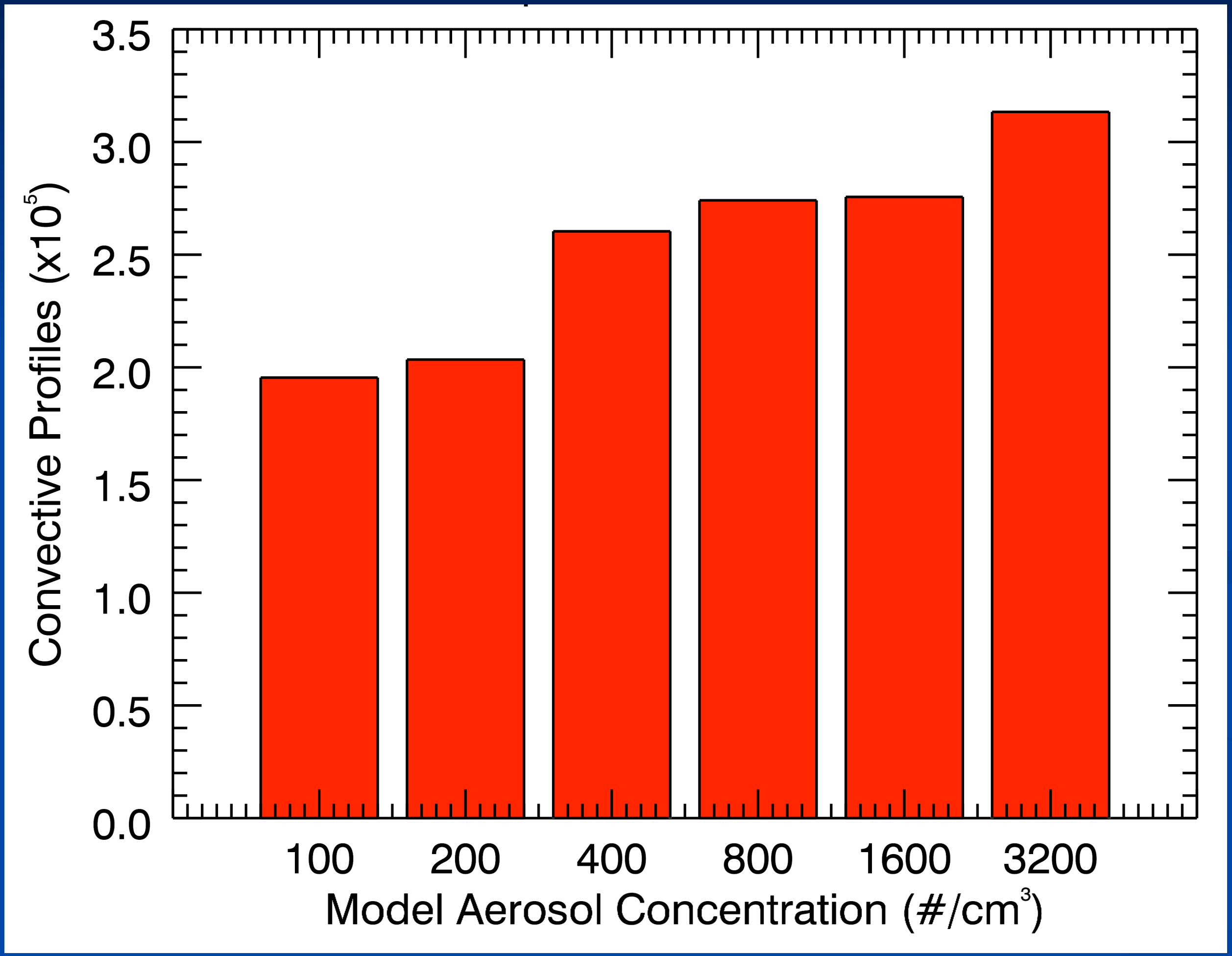
Congestus Mode
Mixed response

Suppression of shallow cloud precipitation offset by increases in deep convective precipitation

Shallow Convective Mode
Suppressed precipitation

Image Source: CRYSTAL-FACE website

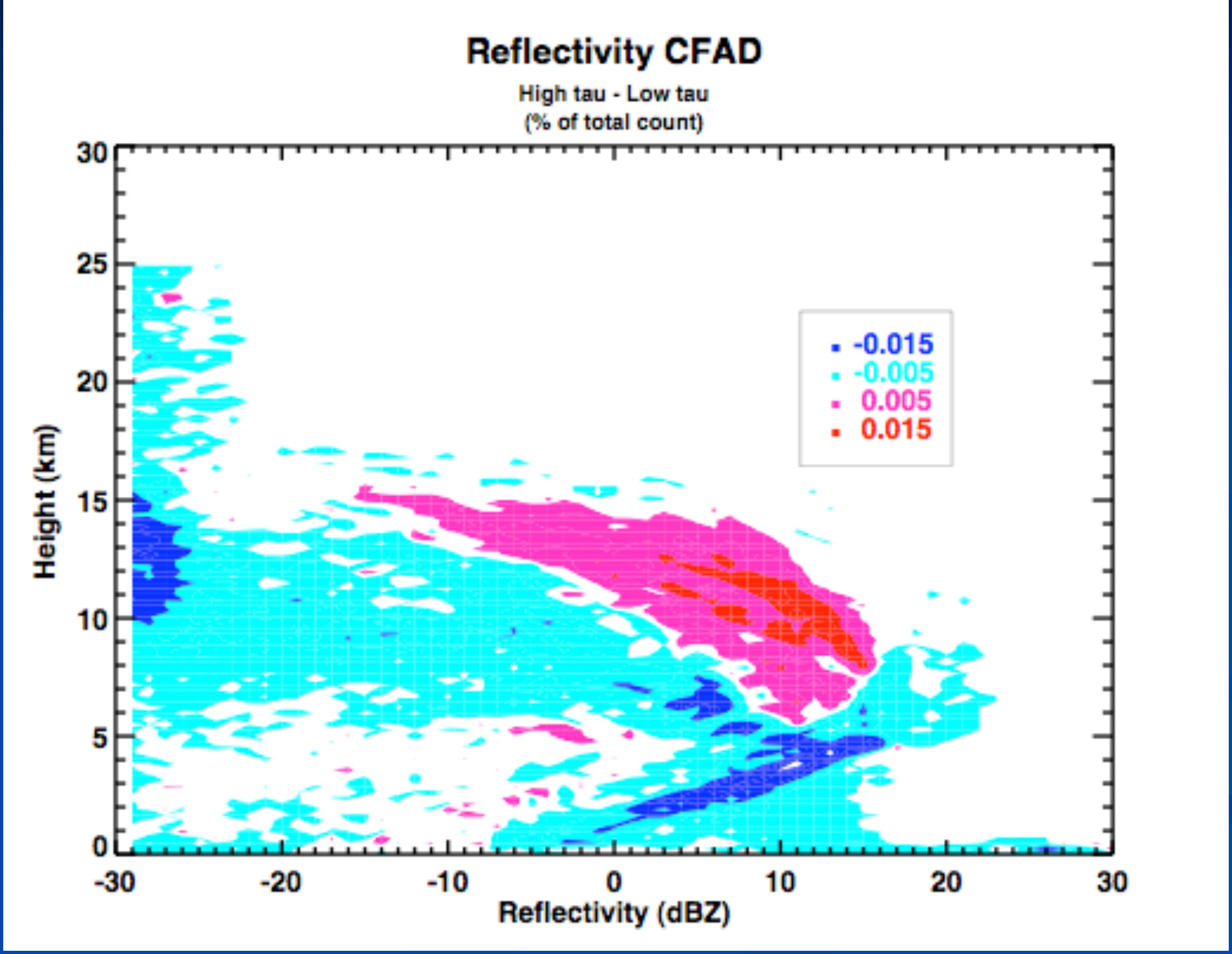
Deep Convective Updraft Frequency



- Higher CCN concentration
  - greater number of wider convective updrafts

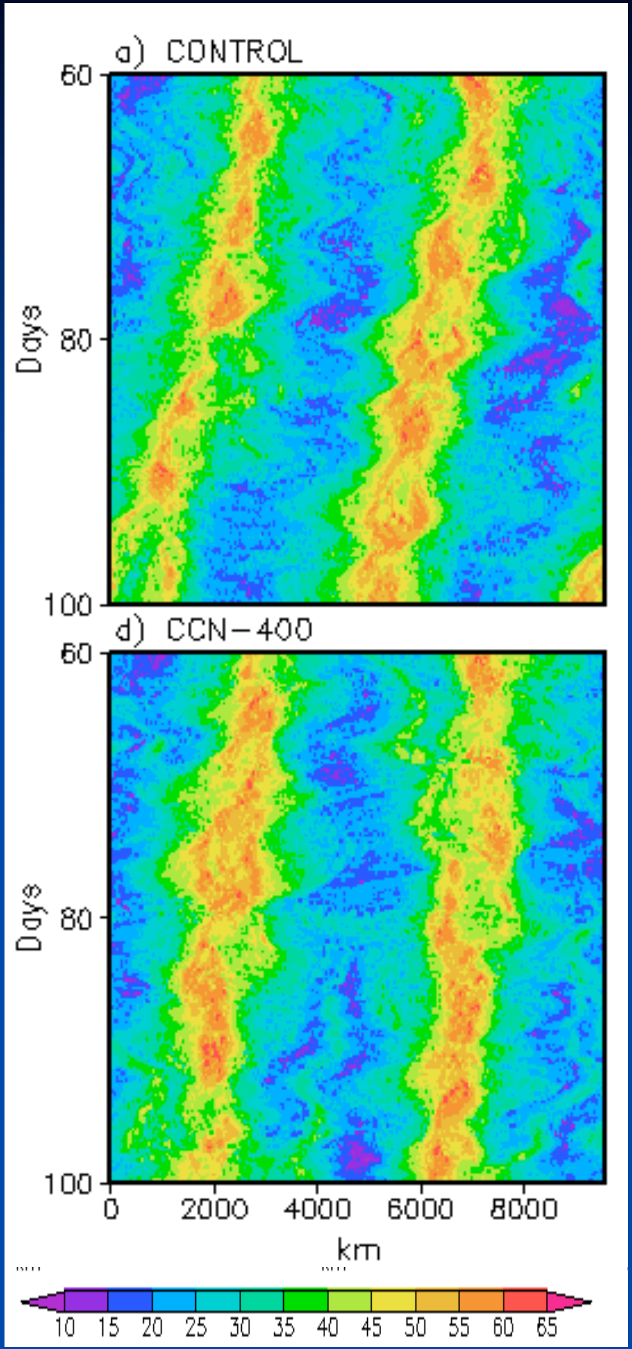
Histogram of deep convective profiles (Storer and van den Heever, 2012)

Dynamic Forcing – CloudSat Evidence



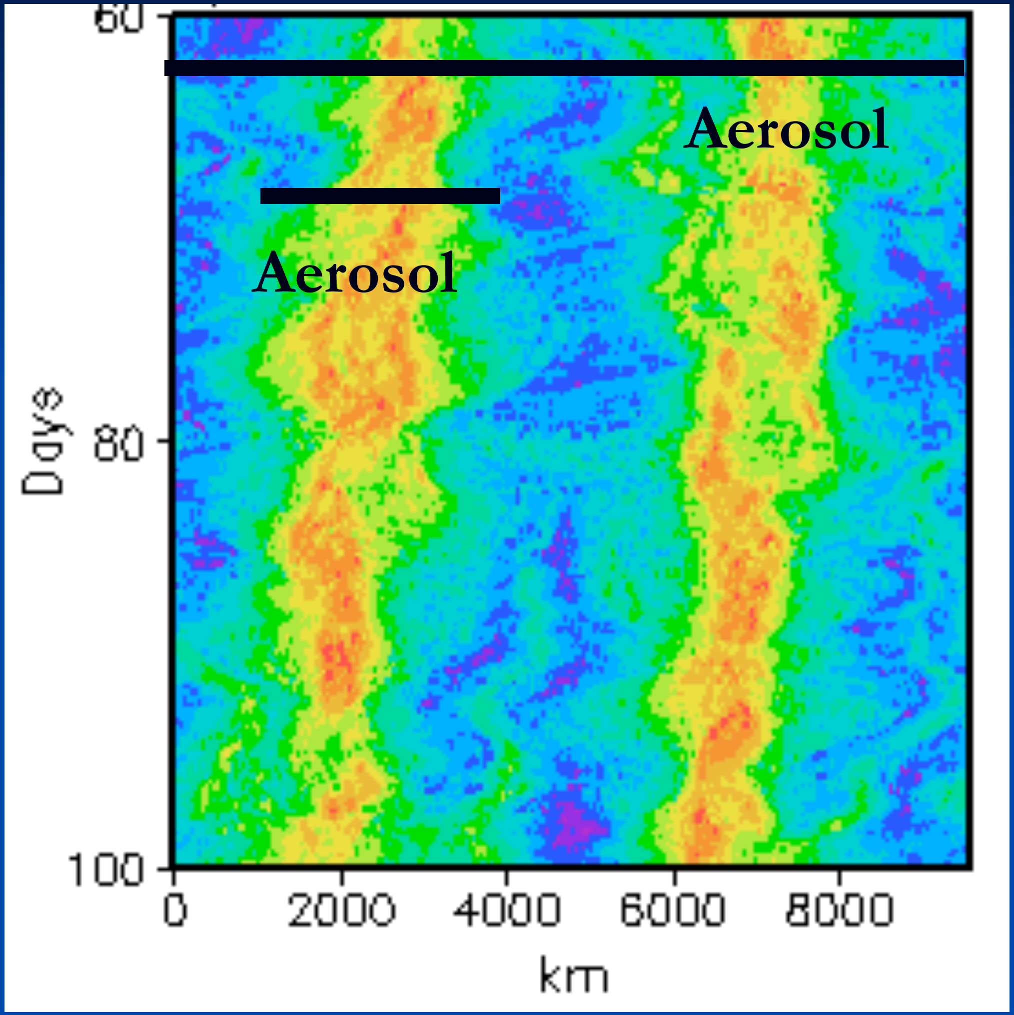
Convective Organization

- Self-sustaining moist and dry bands
- Organization very similar between Control and Aerosol experiments



Hovmuller plot of vertically-integrated water vapor (mm) for the Control experiment and domain-wide aerosol experiments (after van den Heever et al., 2011)

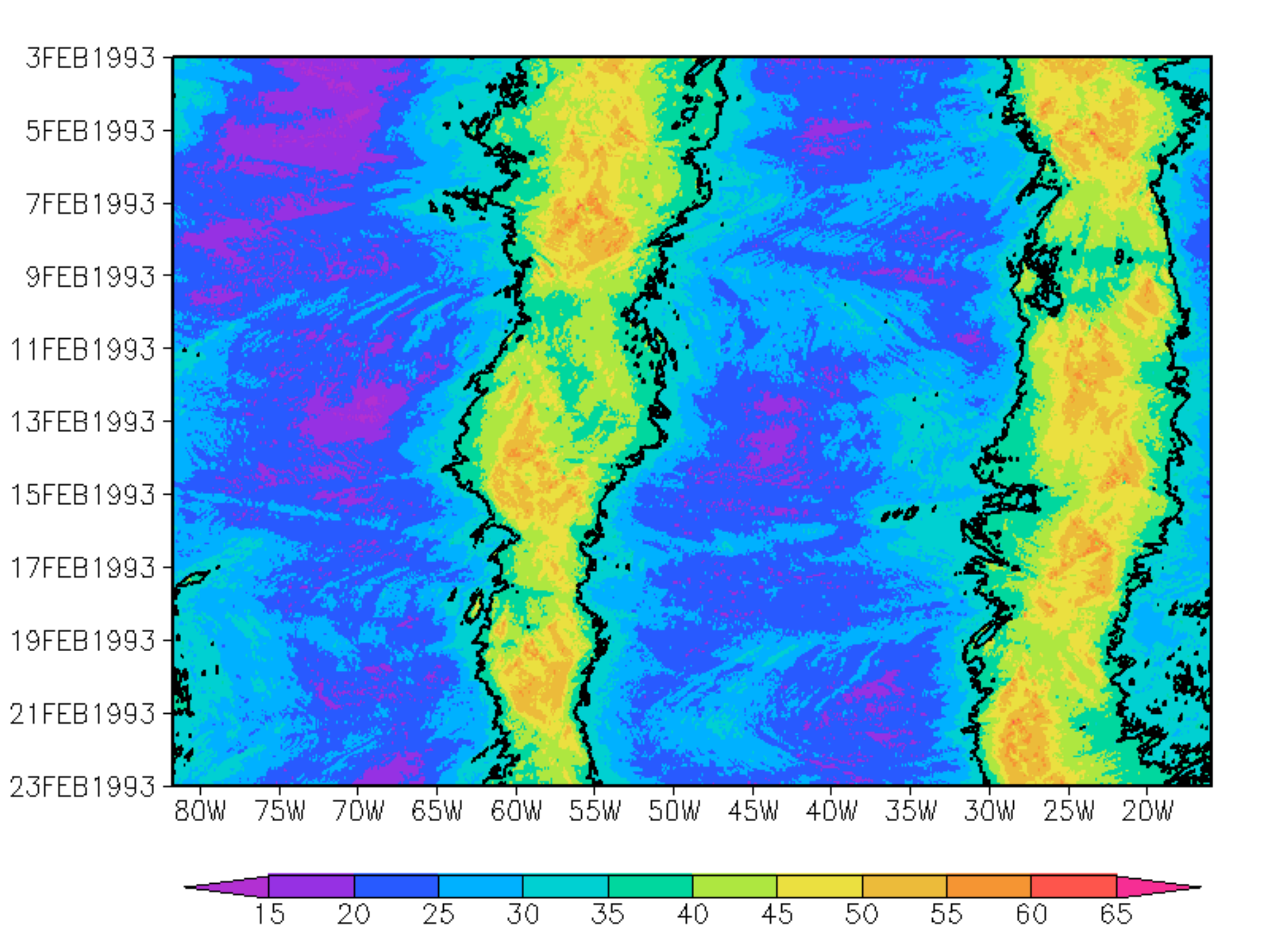
New Experiment Setup



Hovmuller plot of vertically-integrated water vapor (mm) for the Control experiment

- Control
  - Constant clean background
- Polluted Exp
  - 400 cc^{-1} in region of western band

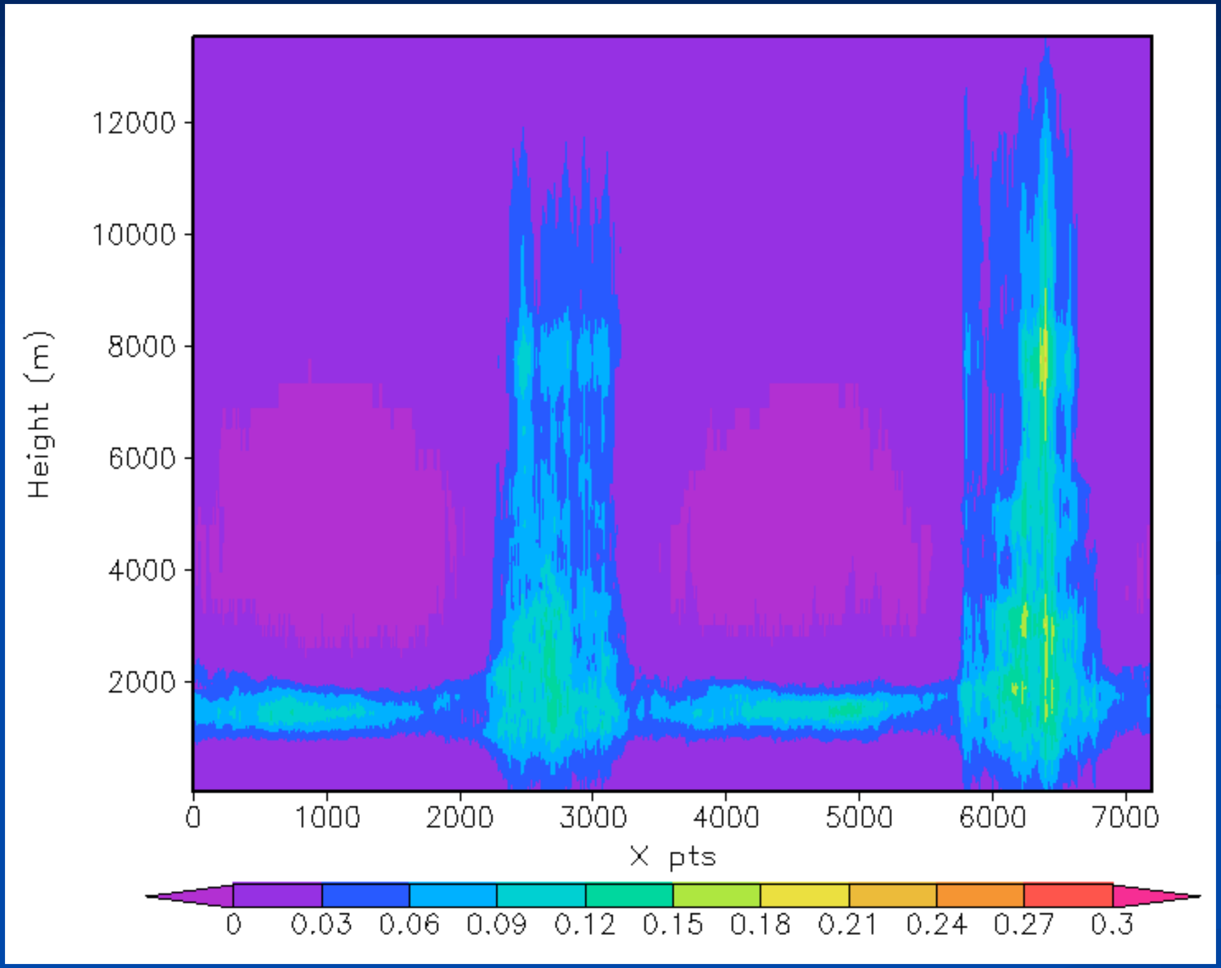
Control – Convective Organization



- Relatively similar moist bands

Hovmuller plot of vertically-integrated water vapor (mm) for the Control experiment

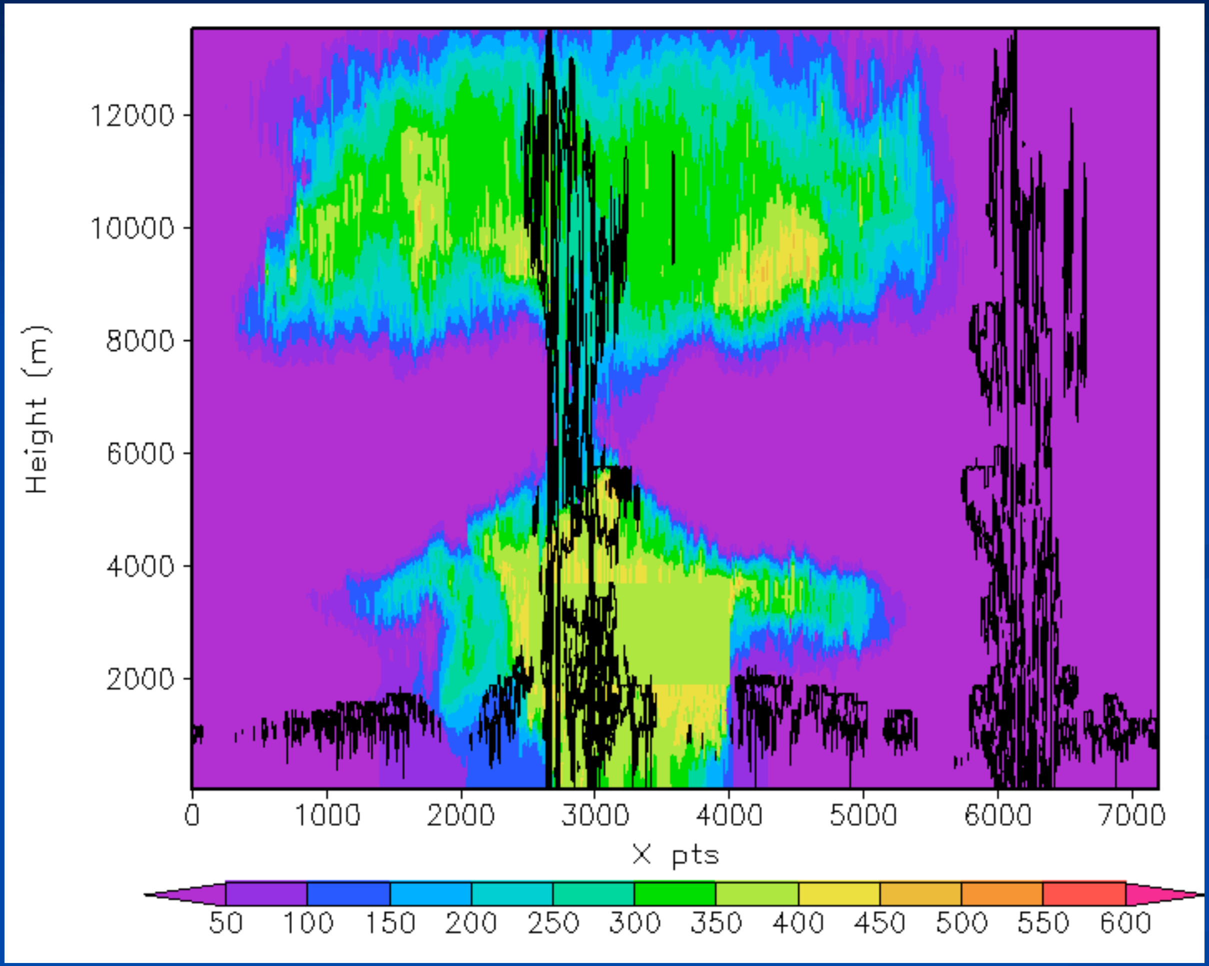
Control – Vertical Structure



20-day average of total condensate (g/kg) for the Control experiment

- Vertical structure of bands relatively similar
- East band slightly deeper

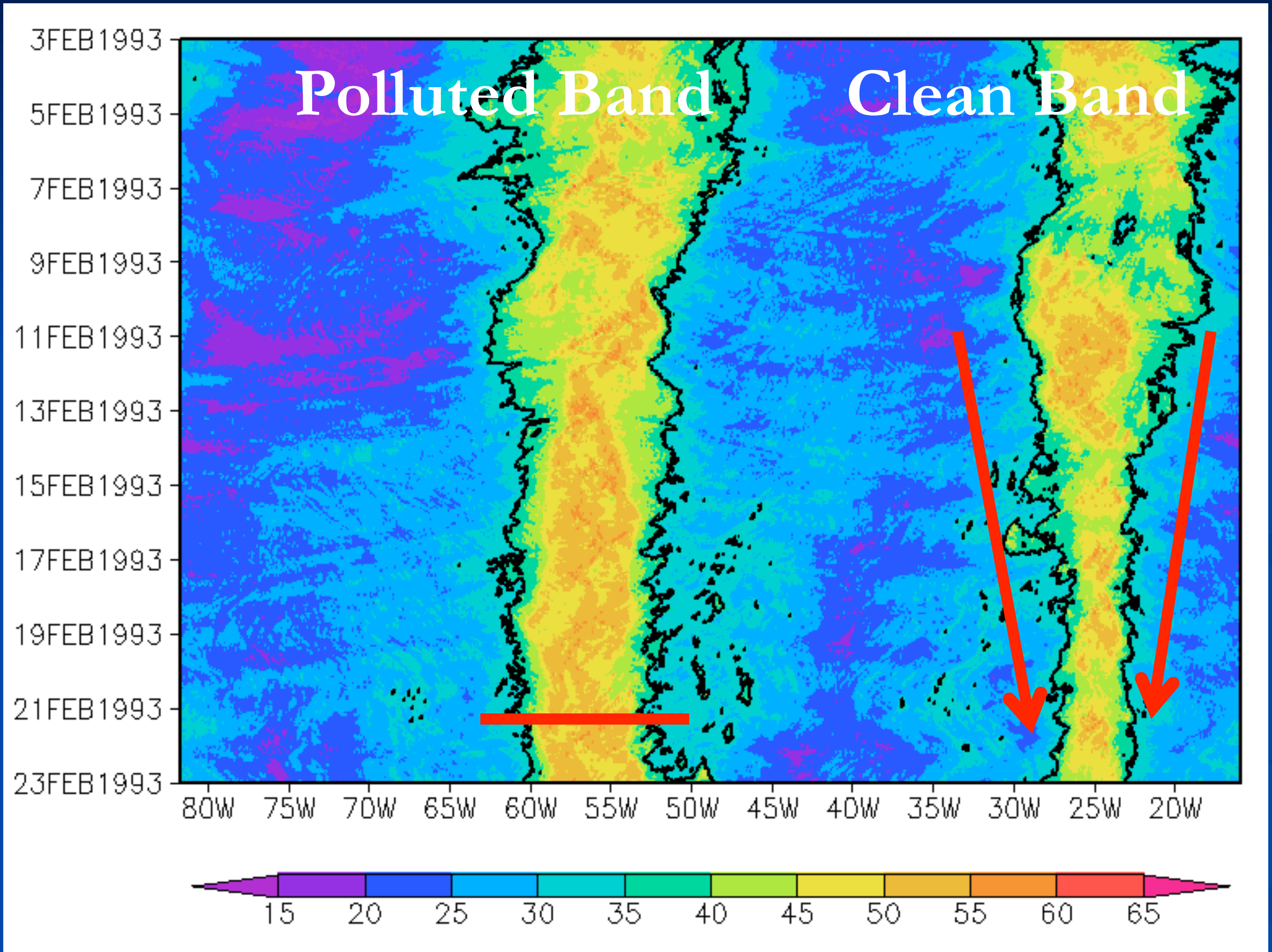
Aerosol Experiment



Aerosol concentration (color, /cc) superimposed on total condensate (g/kg) for the aerosol experiment after 10 days

- Aerosol distributed throughout the western band

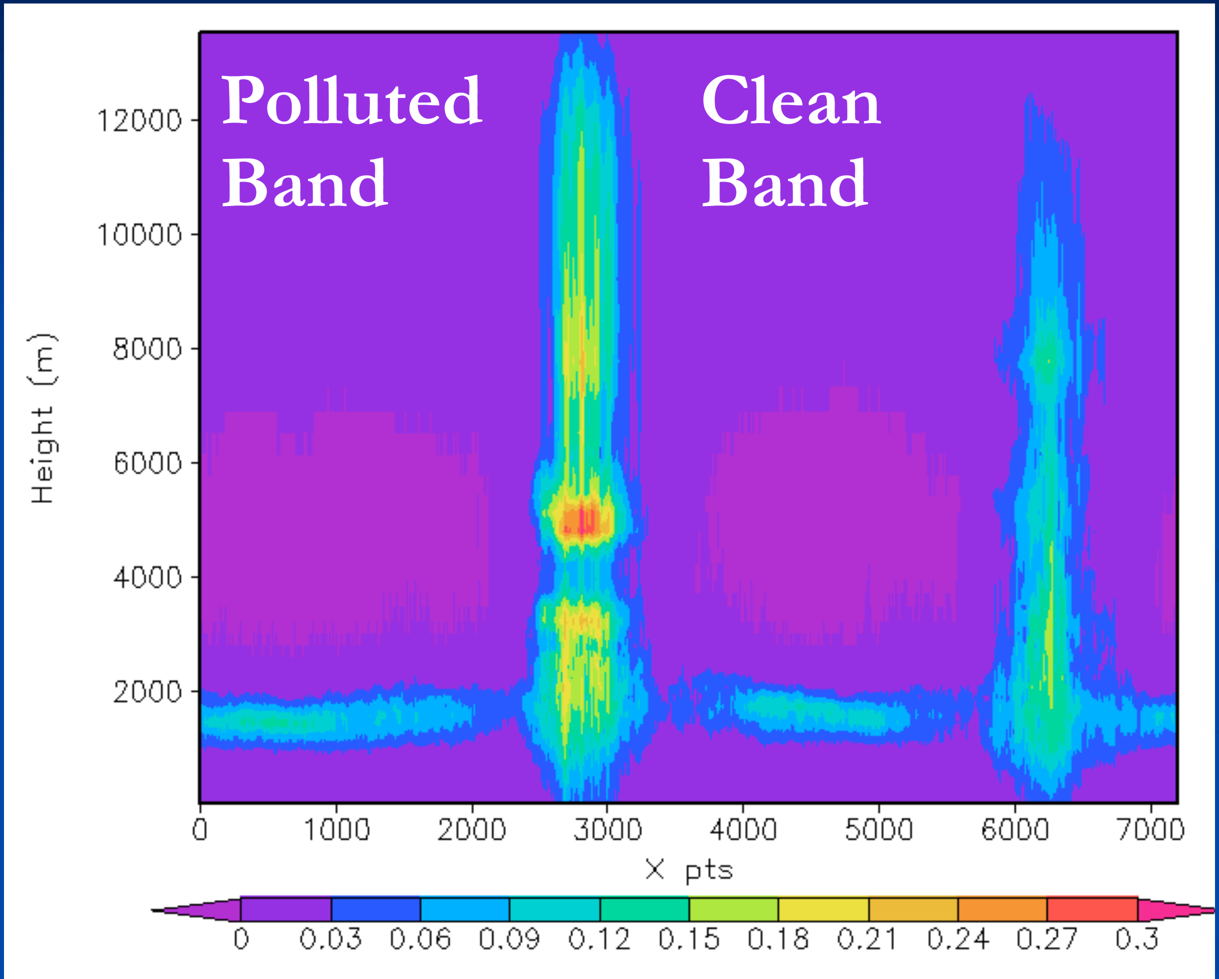
Aerosol – Convective Organization



Hovmuller plot of vertically-integrated water vapor (mm) for the Aerosol Experiment

- Moist bands quite different
- “Clean” band narrows with time
- “Polluted” band wider than in Control

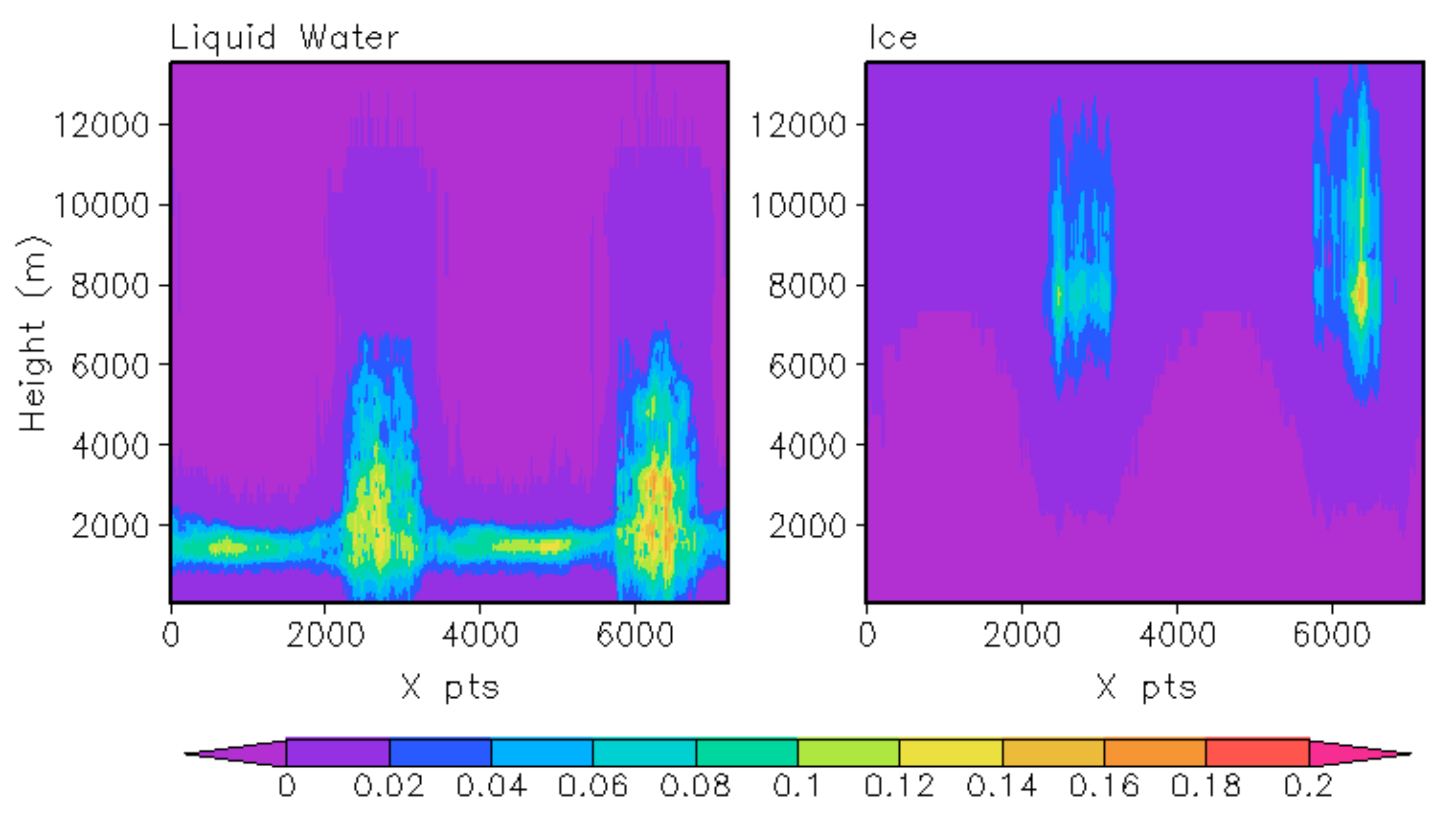
Aerosol Exp – Vertical Structure



20-day average of total condensate (g/kg) for the Aerosol Experiment

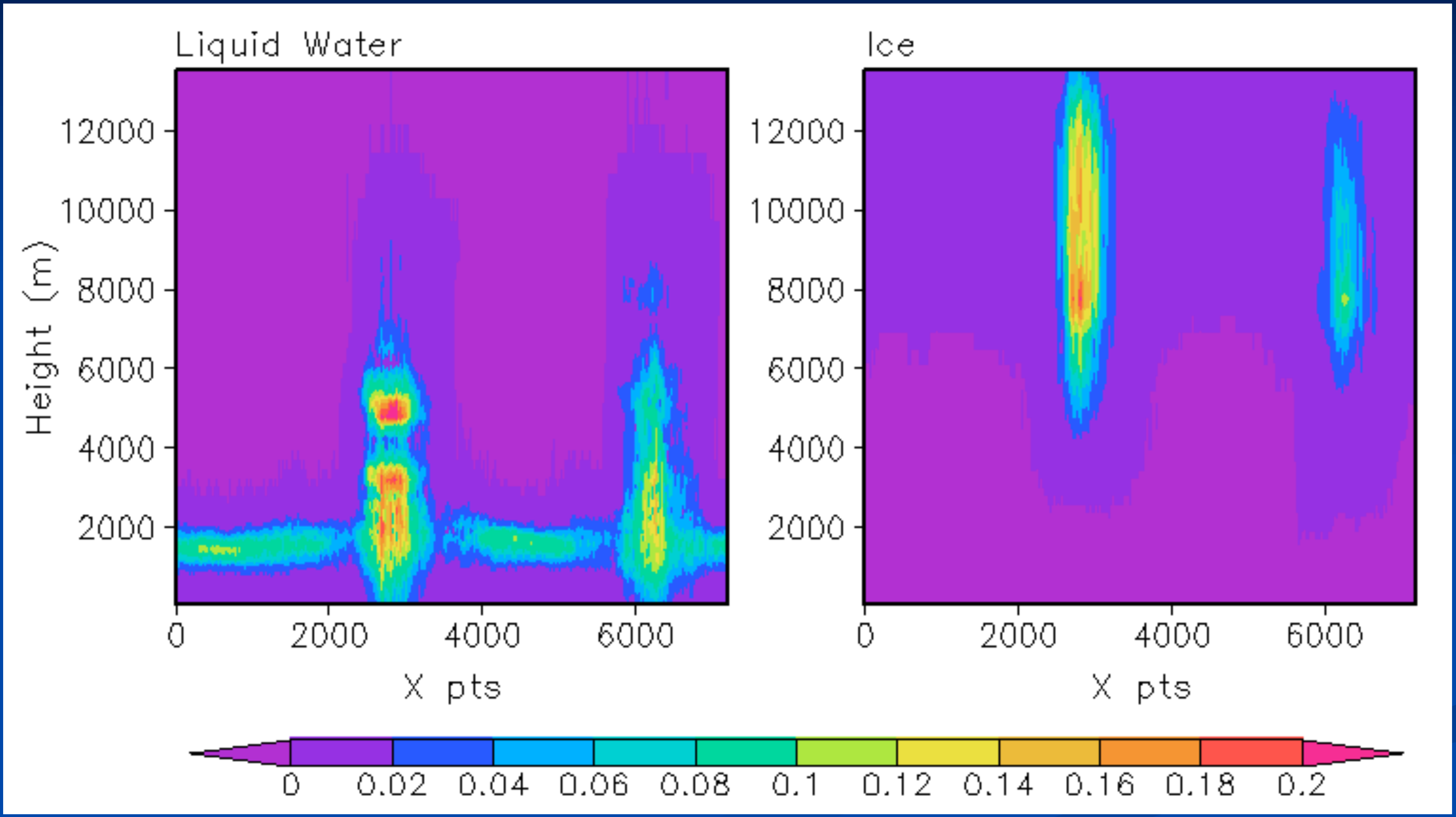
- Vertical structure of bands very different
- Polluted band – greater total condensate and deeper band
- Clean band not as deep

Control – Liquid Water and Ice



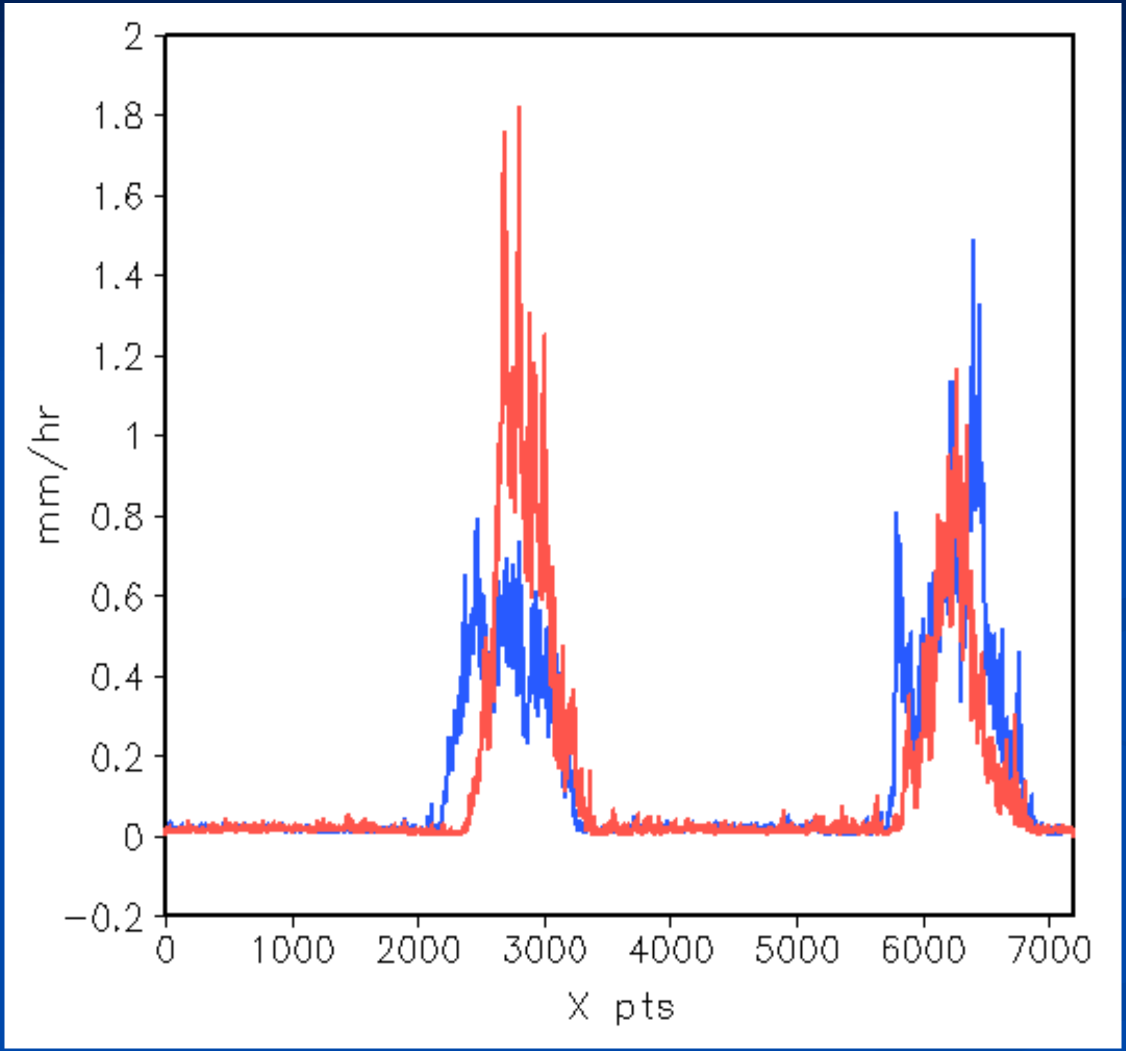
20-day average of liquid water and ice (g/kg) for the Control Experiment

Aerosol Exp – Liquid Water and Ice



20-day average of liquid water and ice (g/kg) for the Aerosol Experiment

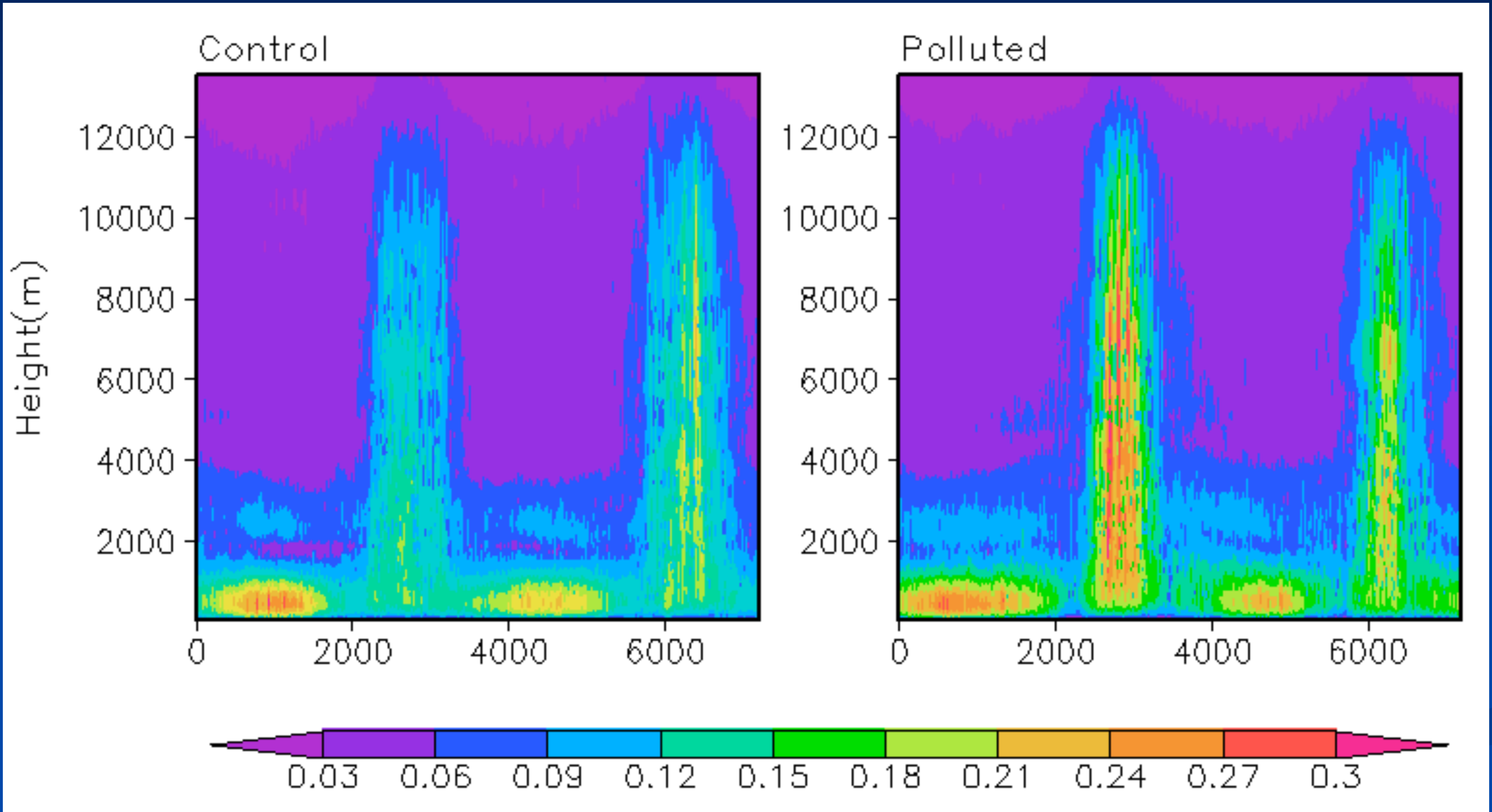
Precipitation Rates



20-day average of precipitation rates (mm/hr) for the control (blue) and aerosol (red) experiments

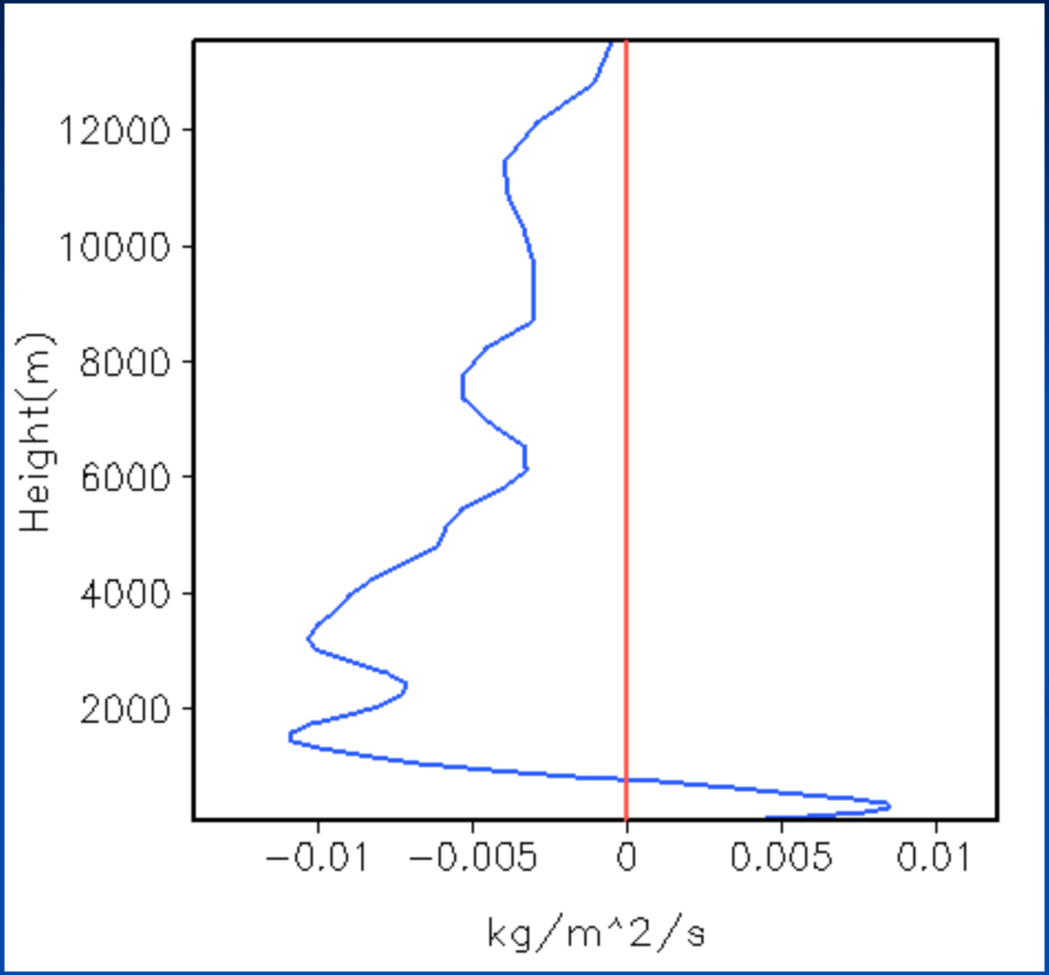
- Polluted band => greater precipitation rates than clean band

Convective Mass Flux



20-day average of the convective mass flux (w>0) (kg/m^2/s)

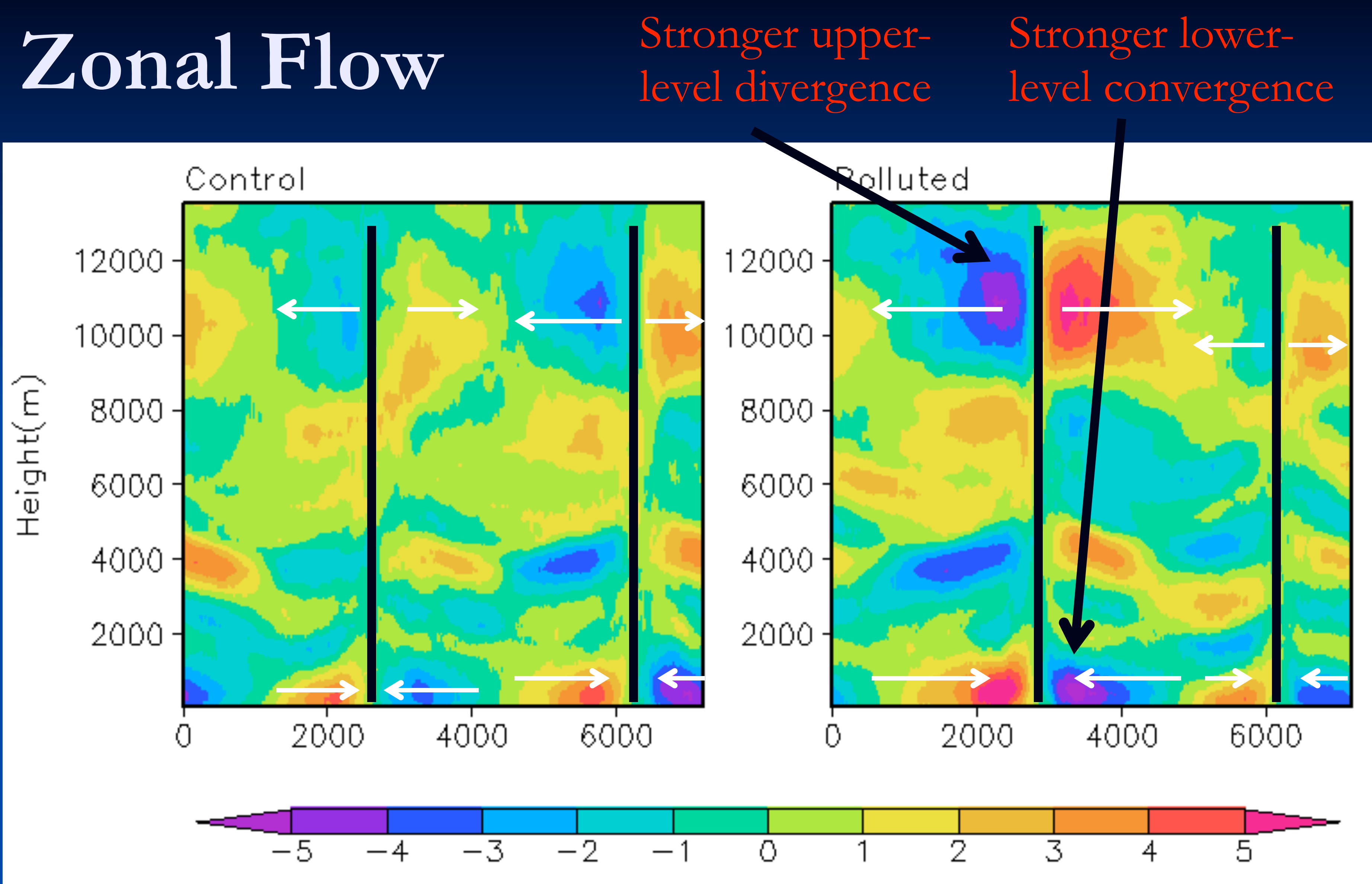
Subsidence Rates



Domain-wide 20-day average subsidence expressed as a difference between Polluted and Control experiments (w<0) (kg/m^2/s)

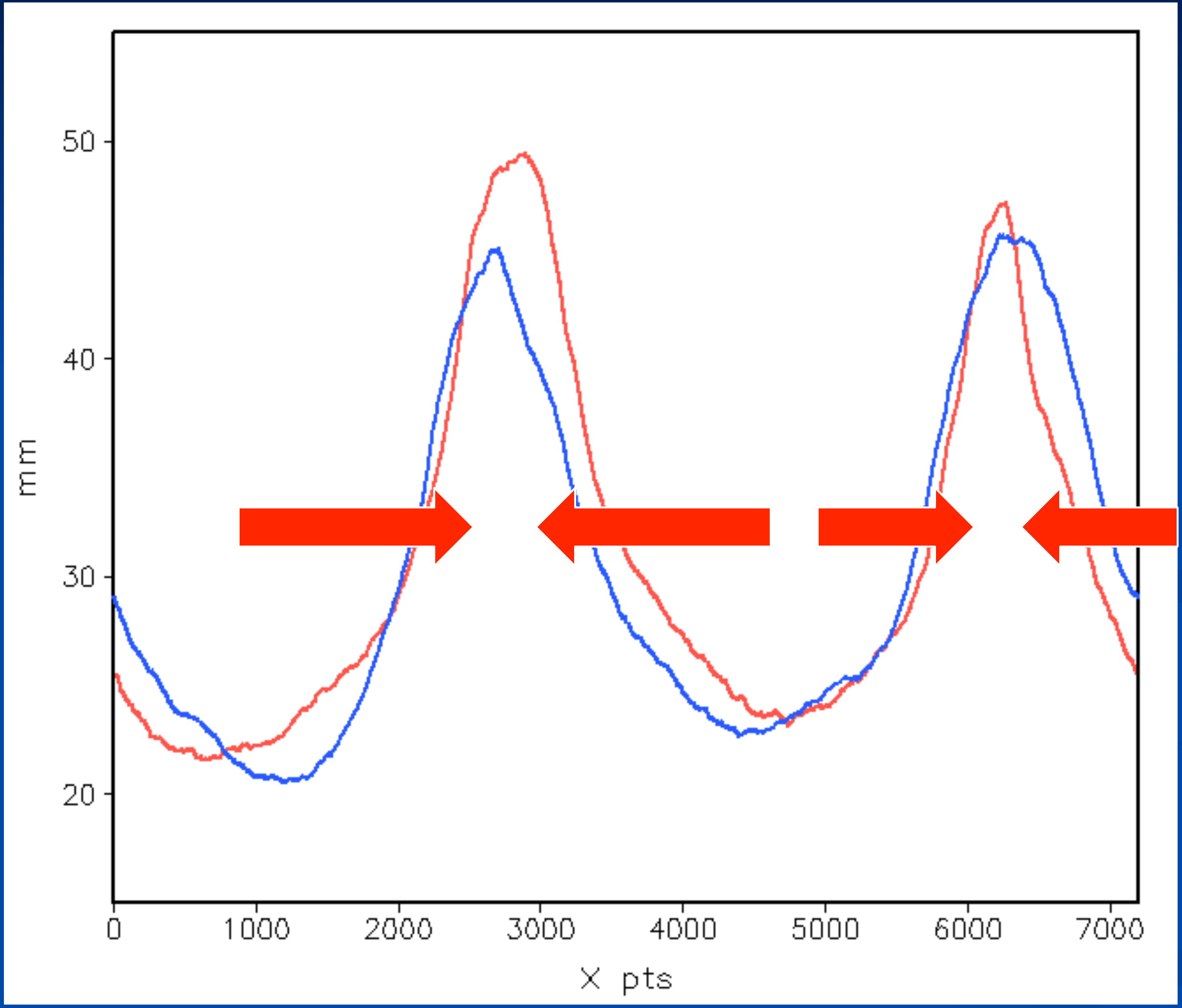
- Greater subsidence domain-wide in aerosol experiment
- Together with enhanced convective mass flux suggests stronger large-scale circulation

Zonal Flow



20-day average of the zonal flow (m/s) for the Control (left) and Polluted (right) experiments

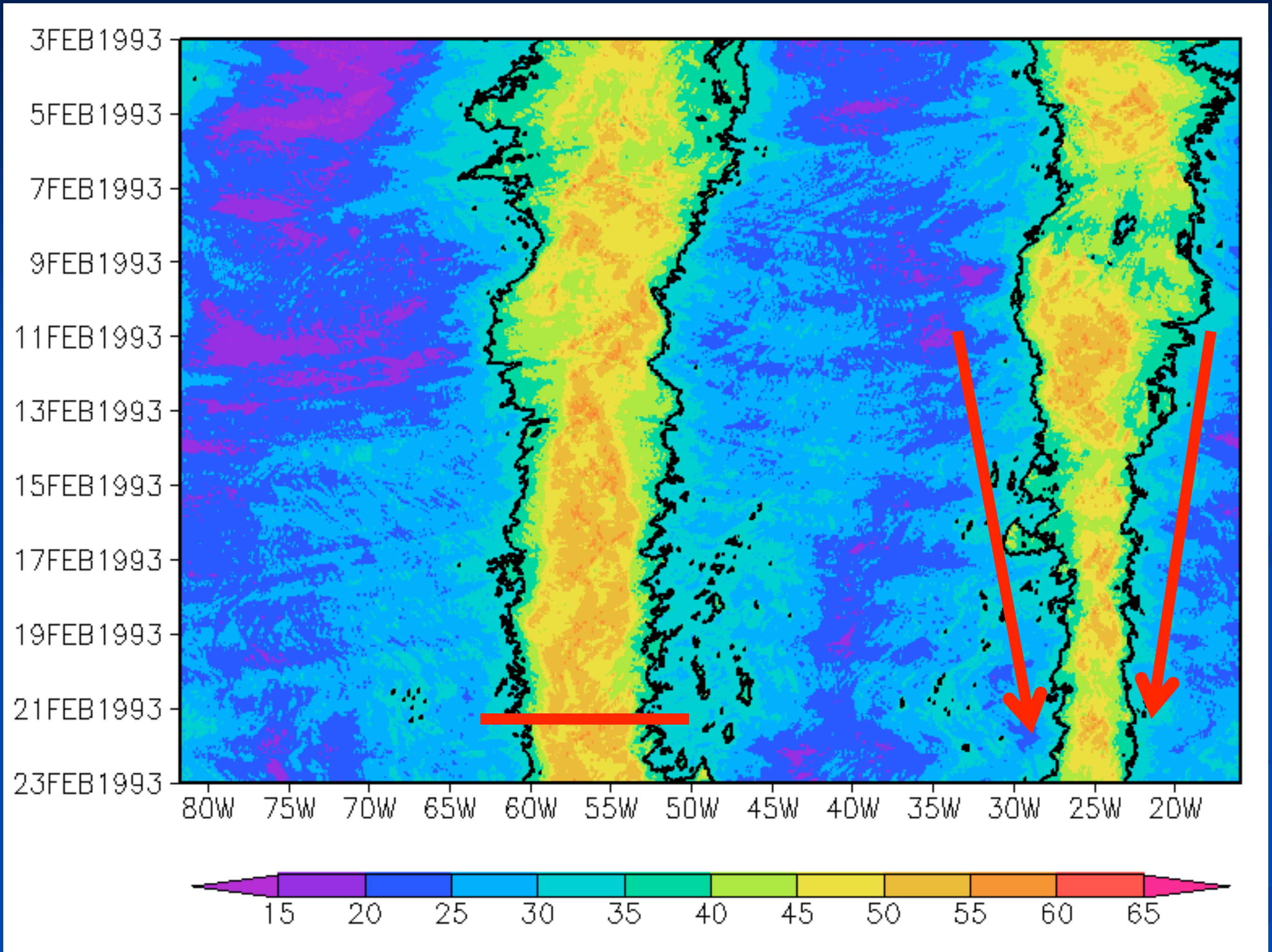
Precipitable Water



20-day average of precipitable water (mm) for the control (blue) and aerosol (red) experiments

- Polluted band => wider with greater PW
- Clean band => narrower with similar PW

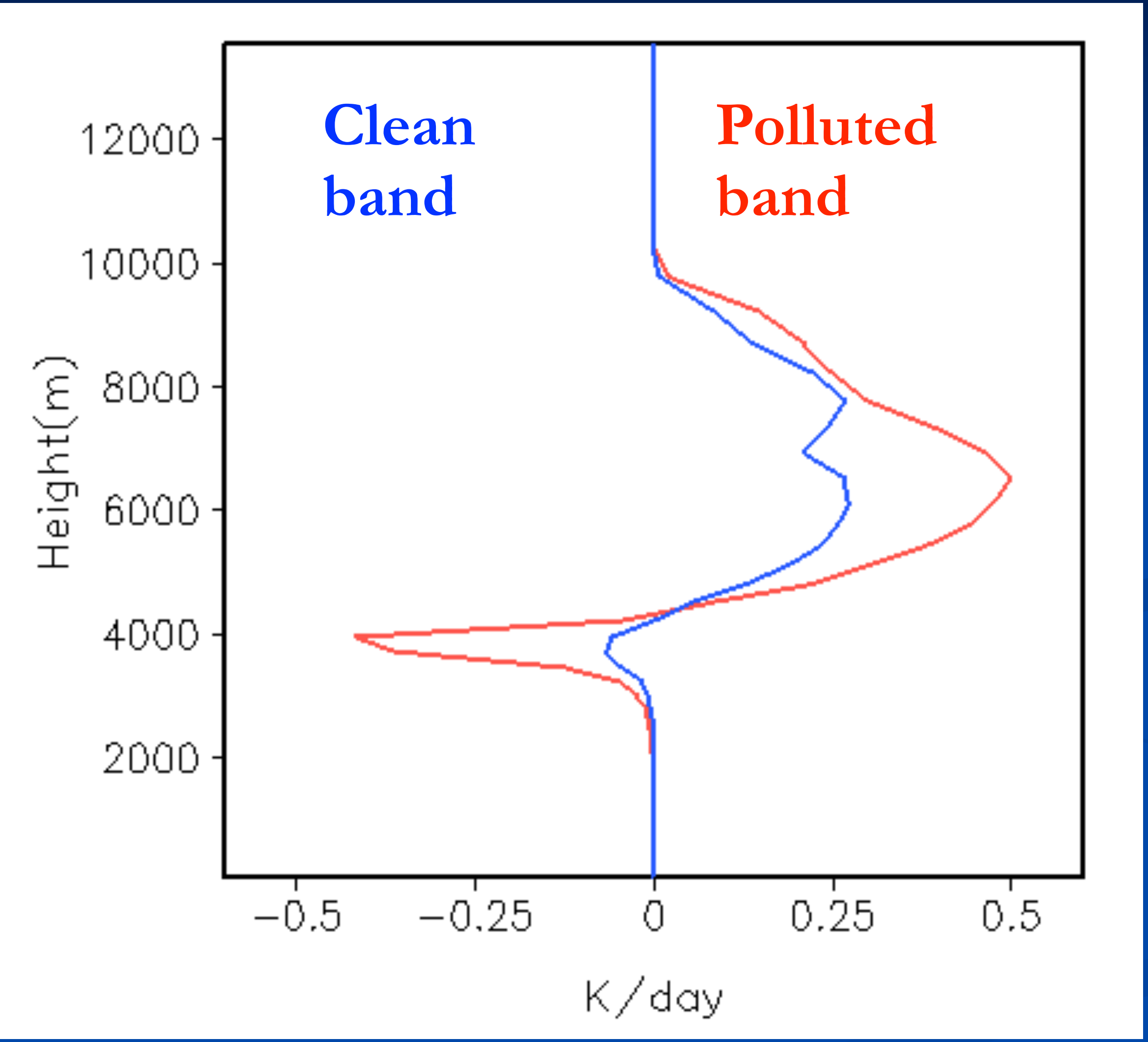
Aerosol – Convective Organization



Hovmuller plot of vertically-integrated water vapor (mm) for the Aerosol Experiment

- Moist bands quite different
- “Clean” band narrows with time
- “Polluted” band wider than in Control

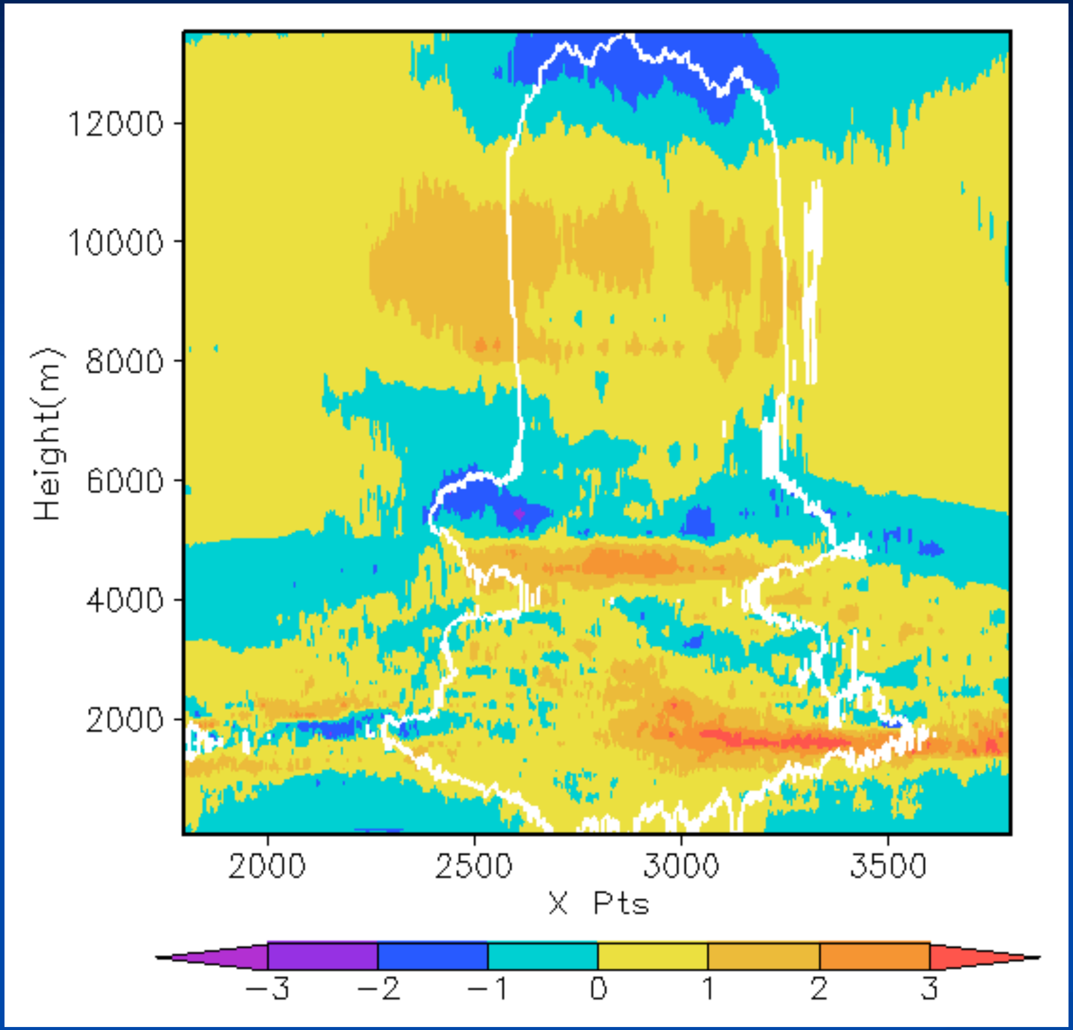
Latent Heat of Freezing



20-day average of latent heat of freezing (K/day) for the polluted (blue) and clean (red) band

- Polluted band => greater latent heat release

Net Radiative Heating Rates

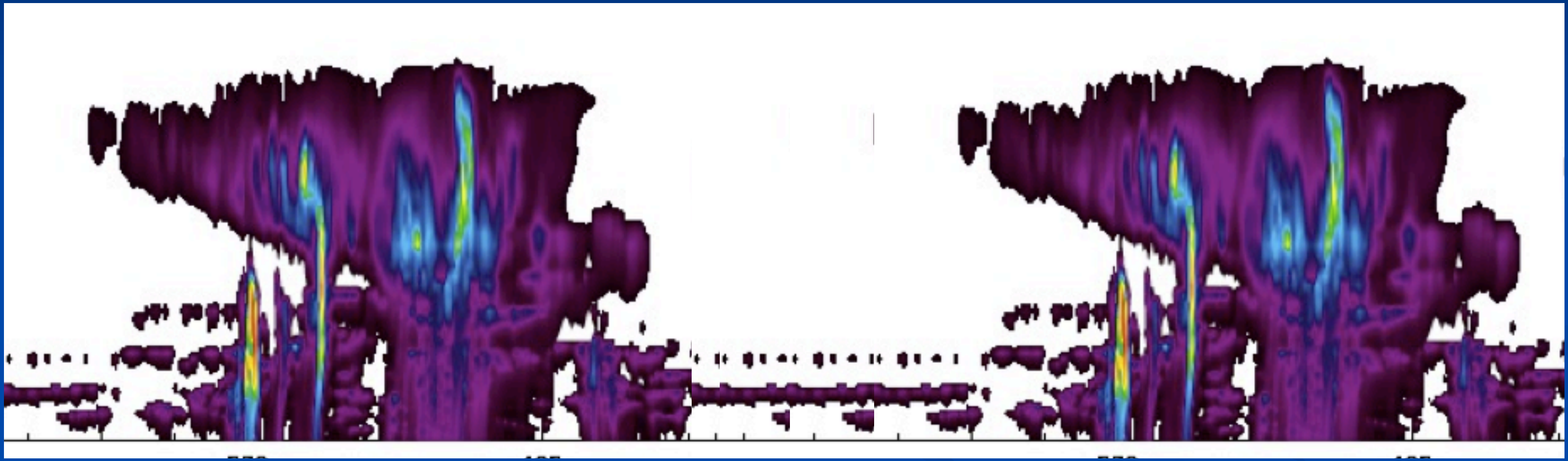


20-day average of the Polluted-Control total radiative heating rate (K/day) for the polluted band

- Polluted experiment => greater net cooling at anvil top
- Gradients in radiative heating
- Need enhanced subsidence to offset cooling (Gray and Jacobson, 1977)

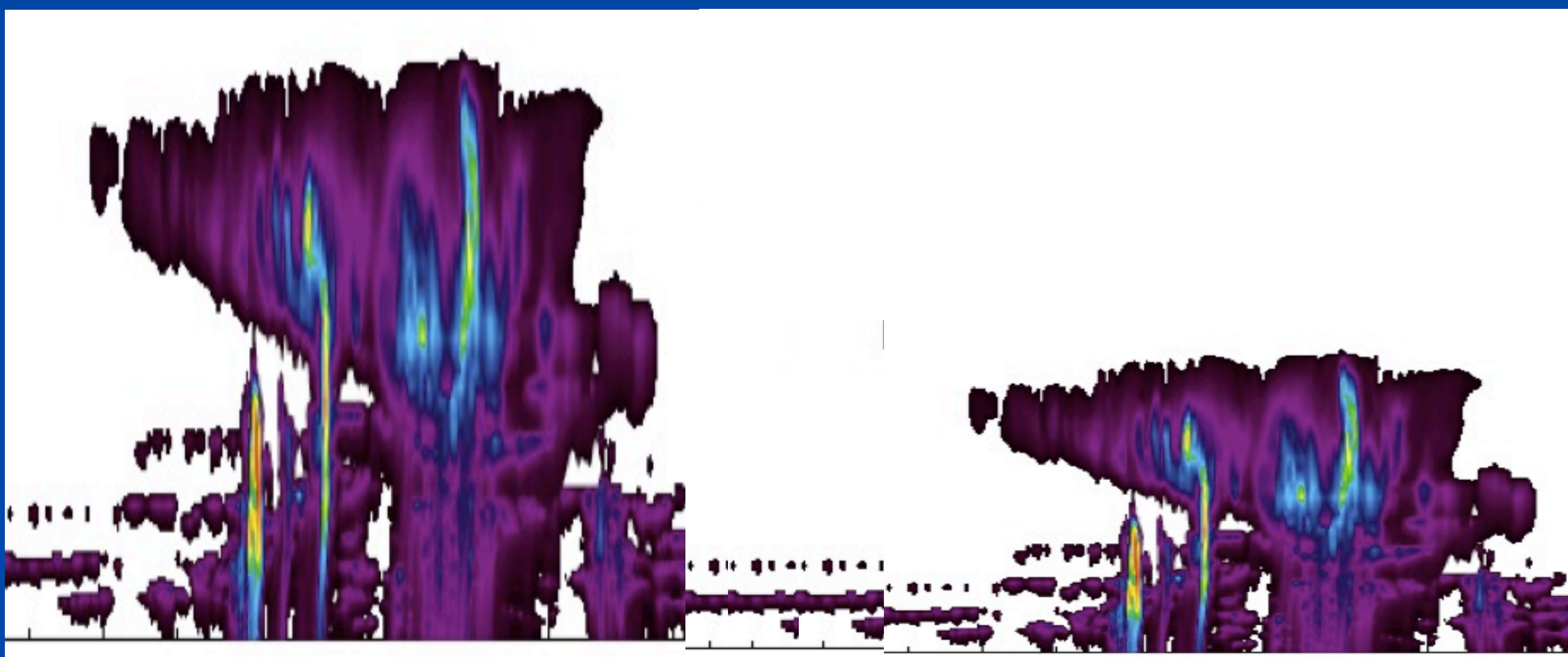
Convective Organization Summary

- Control Experiment
- Moist bands with similar cloud distributions and characteristics



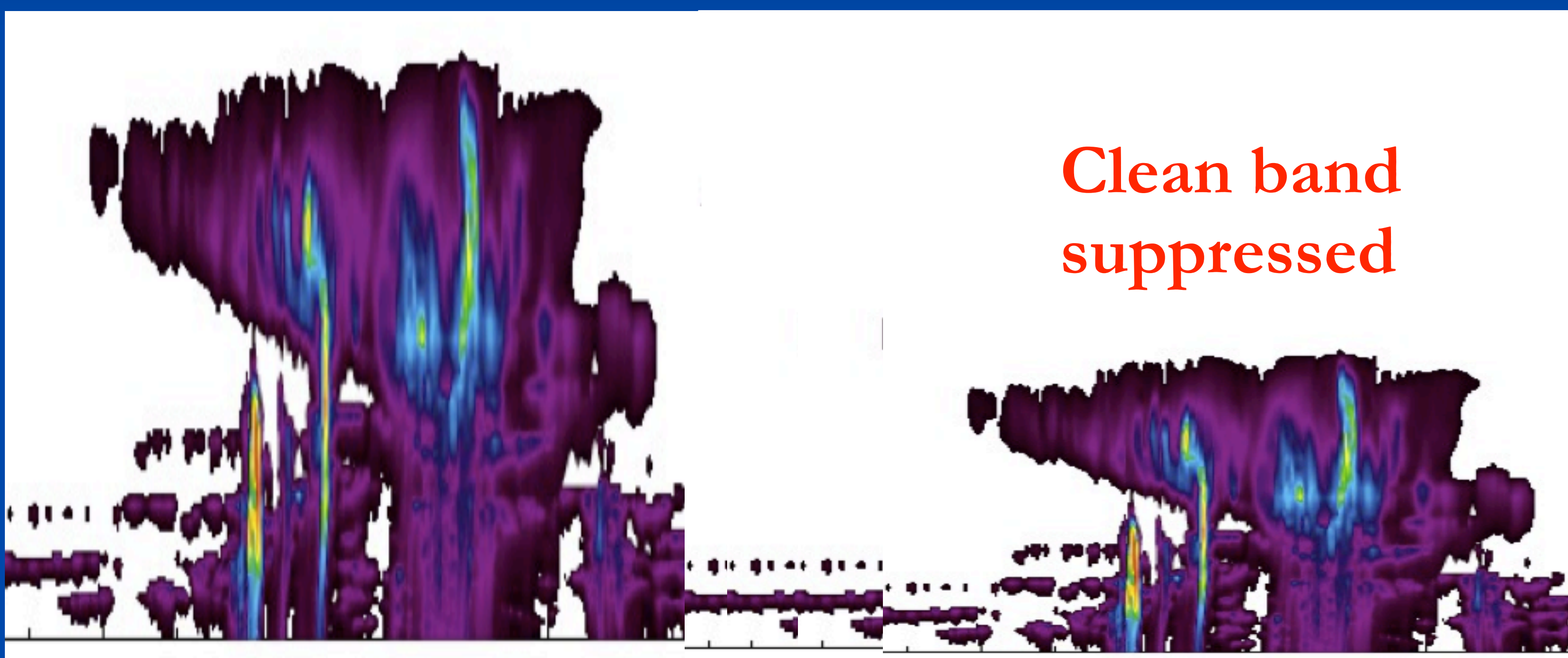
Aerosol Layer

- Deeper convective systems
- Greater ice and liquid water mass
- Greater surface precipitation



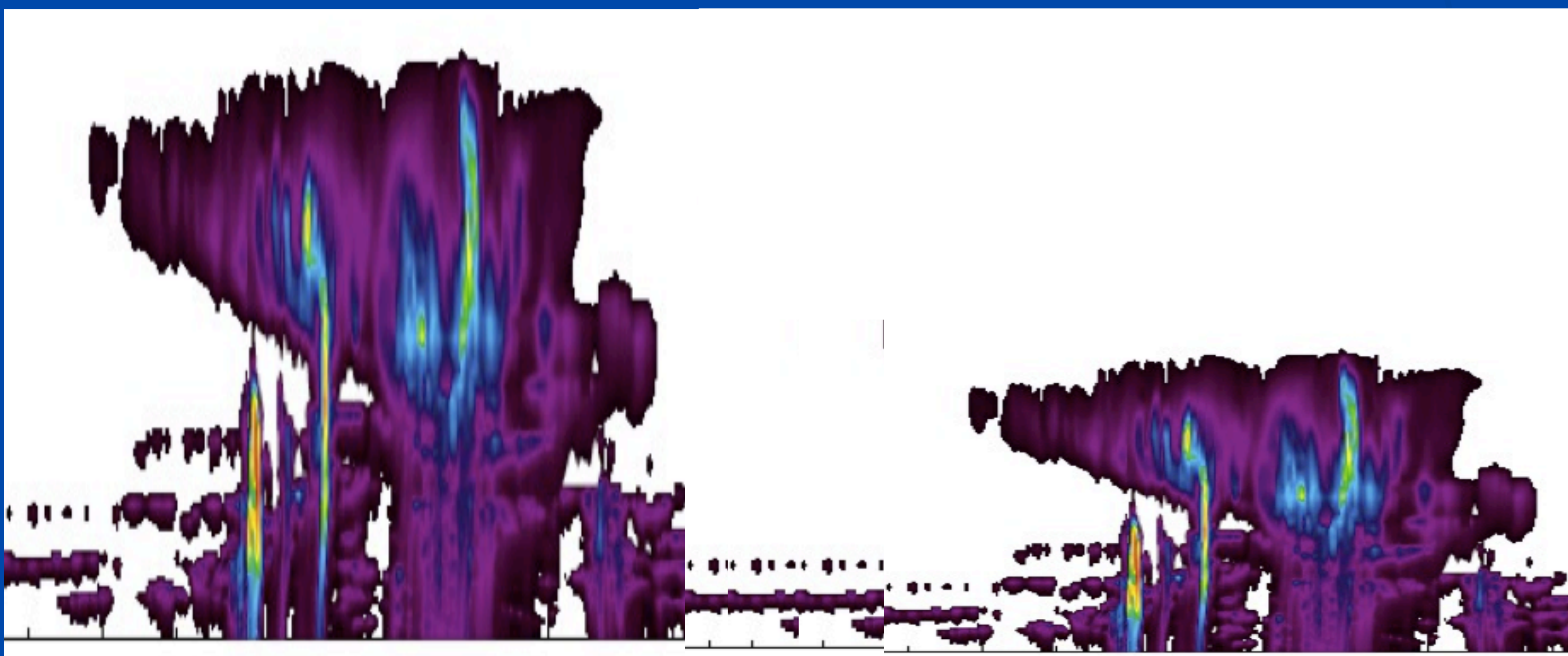
Aerosol Layer

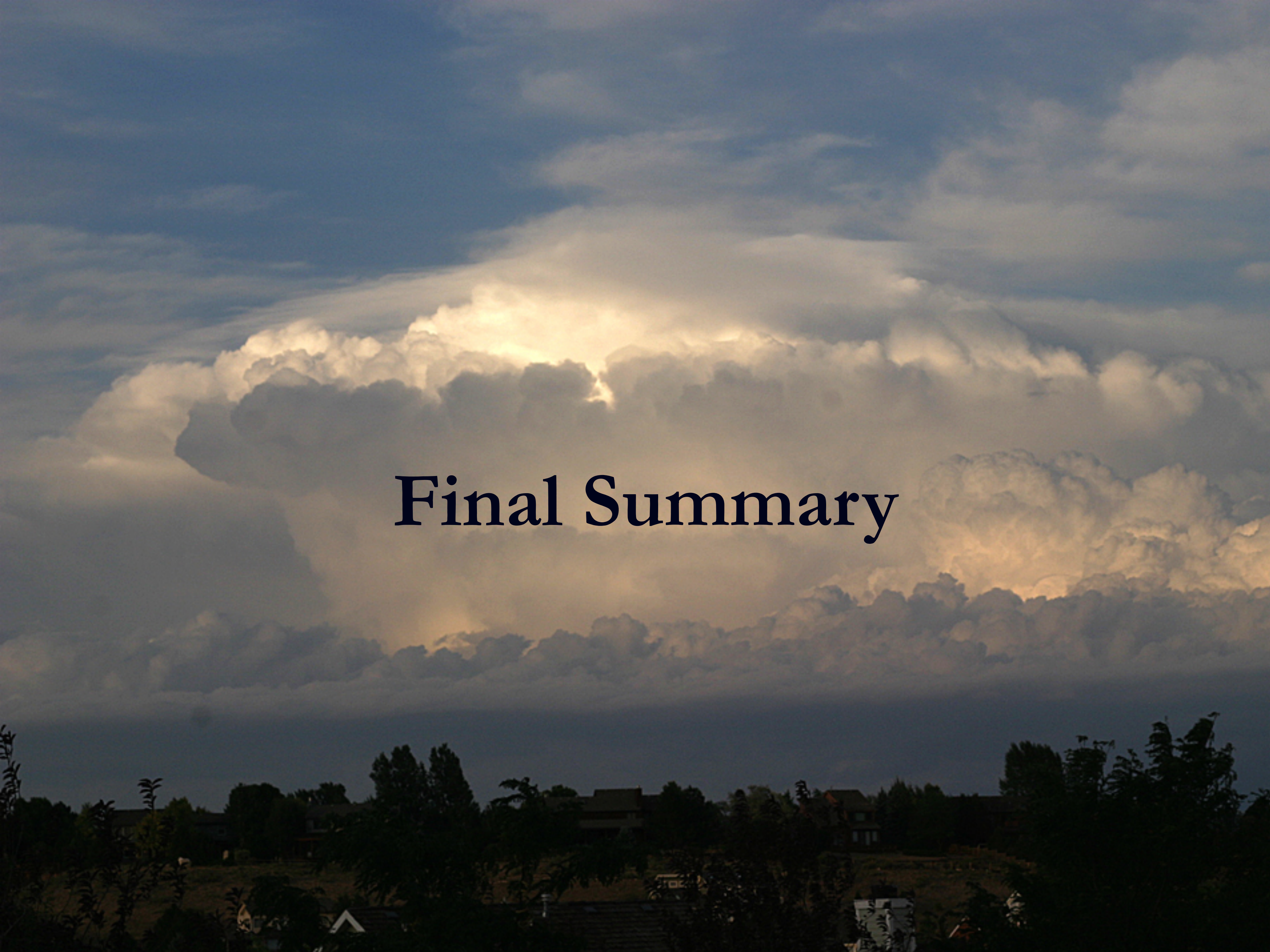
- Greater convective mass flux
- Greater subsidence
- Stronger large-scale circulation
- Broader, more moist regions



Aerosol Layer

- Greater latent heat release
- Greater net radiative cooling at cloud top
- Cold pool impacts
- Aerosol indirect effects => large-scale organization of tropical convective systems




Final Summary

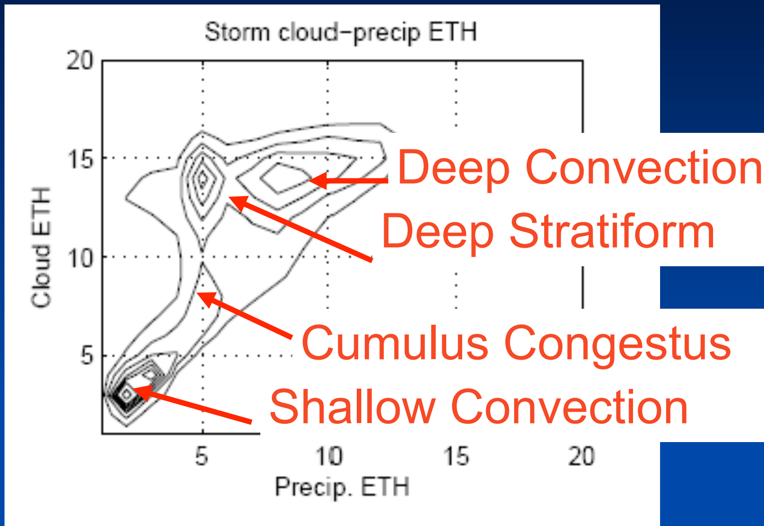
- CRM simulations demonstrate a wide range of storm dynamical responses to changes in the microphysics due aerosol indirect forcing with subsequent feedbacks to the microphysics
  - Cold pools
  - Environmental roles
  - Dust transport
  - System wide responses
  - Anvil forcing
- More field campaigns are needed that measure "the right stuff" for model assessments and comparisons

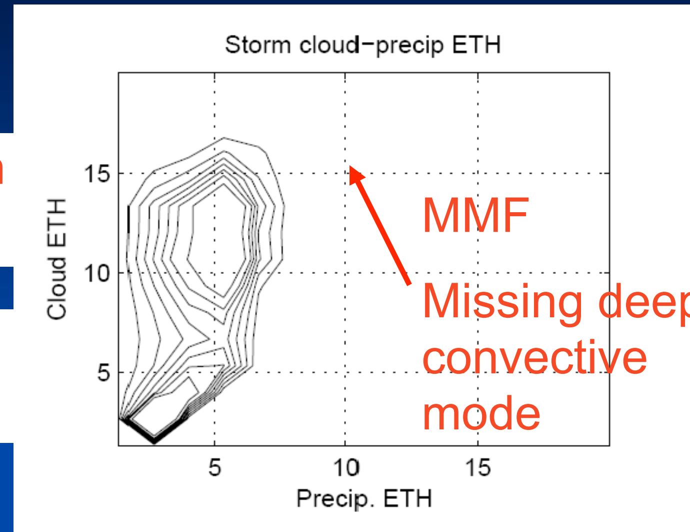

Way Forward …..

Cloud-Precipitation ETH Histograms

CLOUDSAT

MMF Luo et al. (2007)



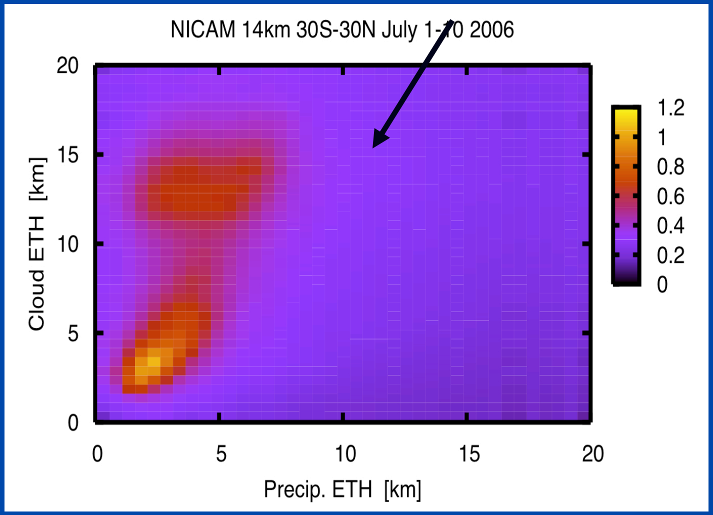


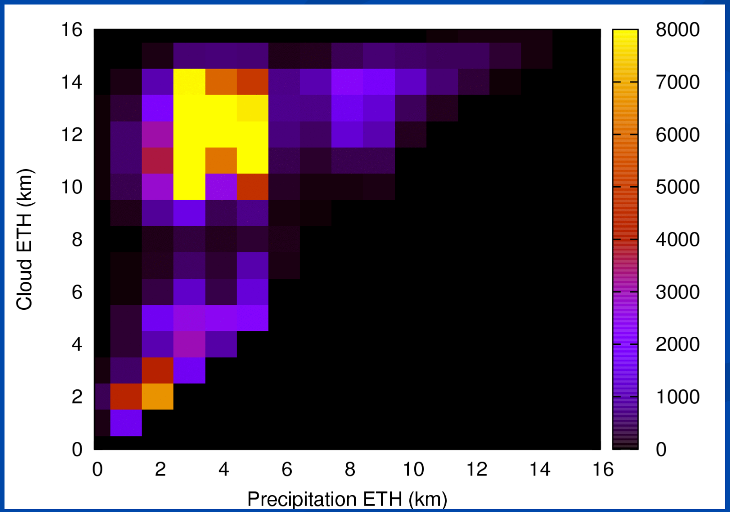
Methodologyby Stephens and Wood (MWR 2007) adapted from Masunaga et al. (JC 2005)

NICAM

Missing deep convective mode

RAMS

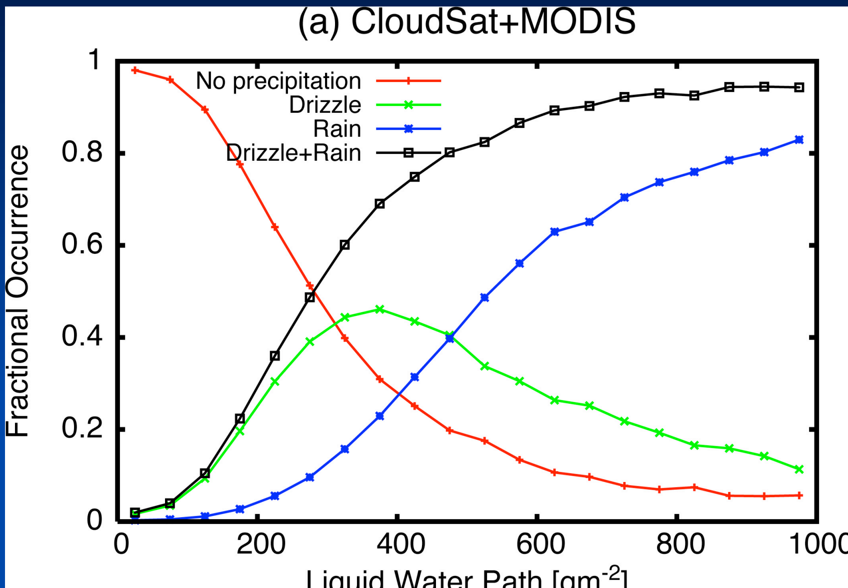


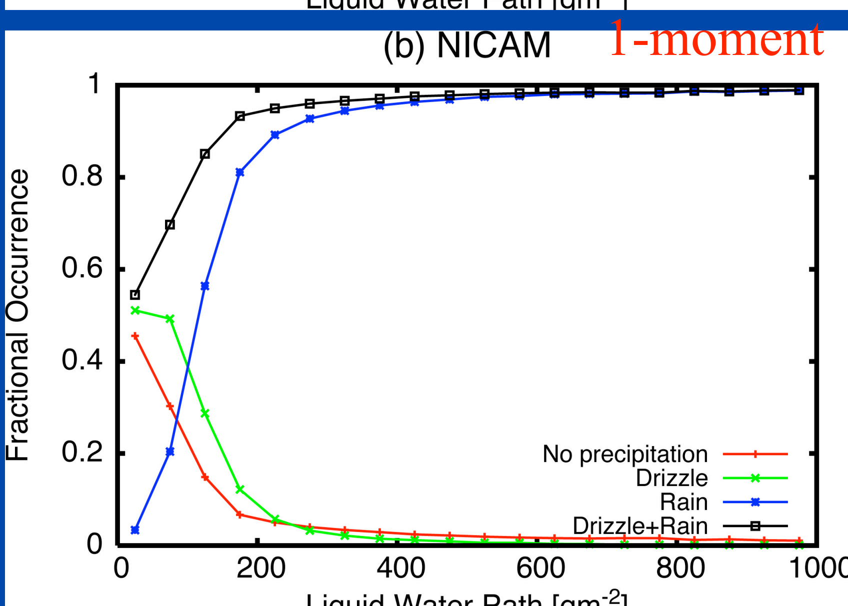


Shallow convection frequency a little low

Suzuki et al. (2007)

Cloud-Drizzle Transitions: Obs and Models



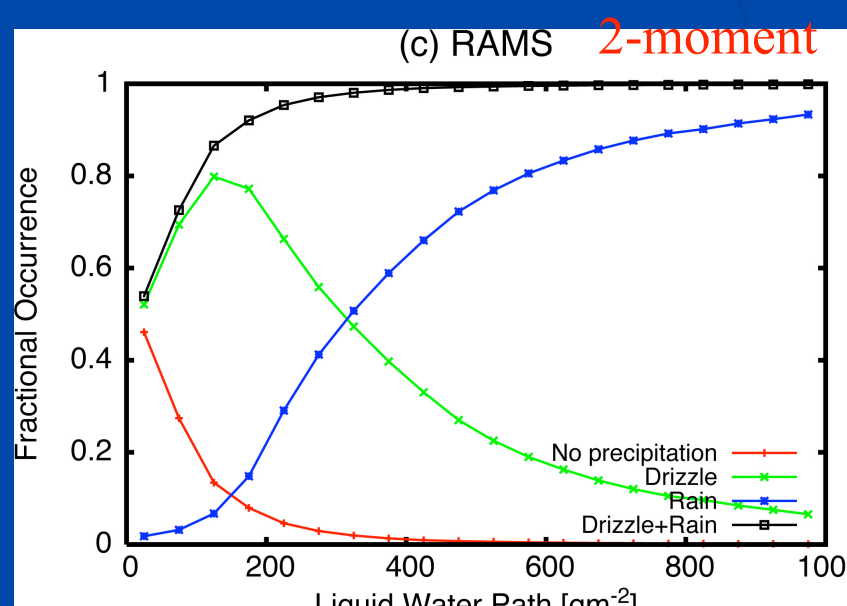


Precipitation categories:

No precipitation: Z_{sfc} < -15dBZ

Drizzle: -15dBZ < Z_{sfc} < 0dBZ

Rain: 0dBZ < Z_{sfc}



Suzuki et al (2011)

Source: University of Arizona

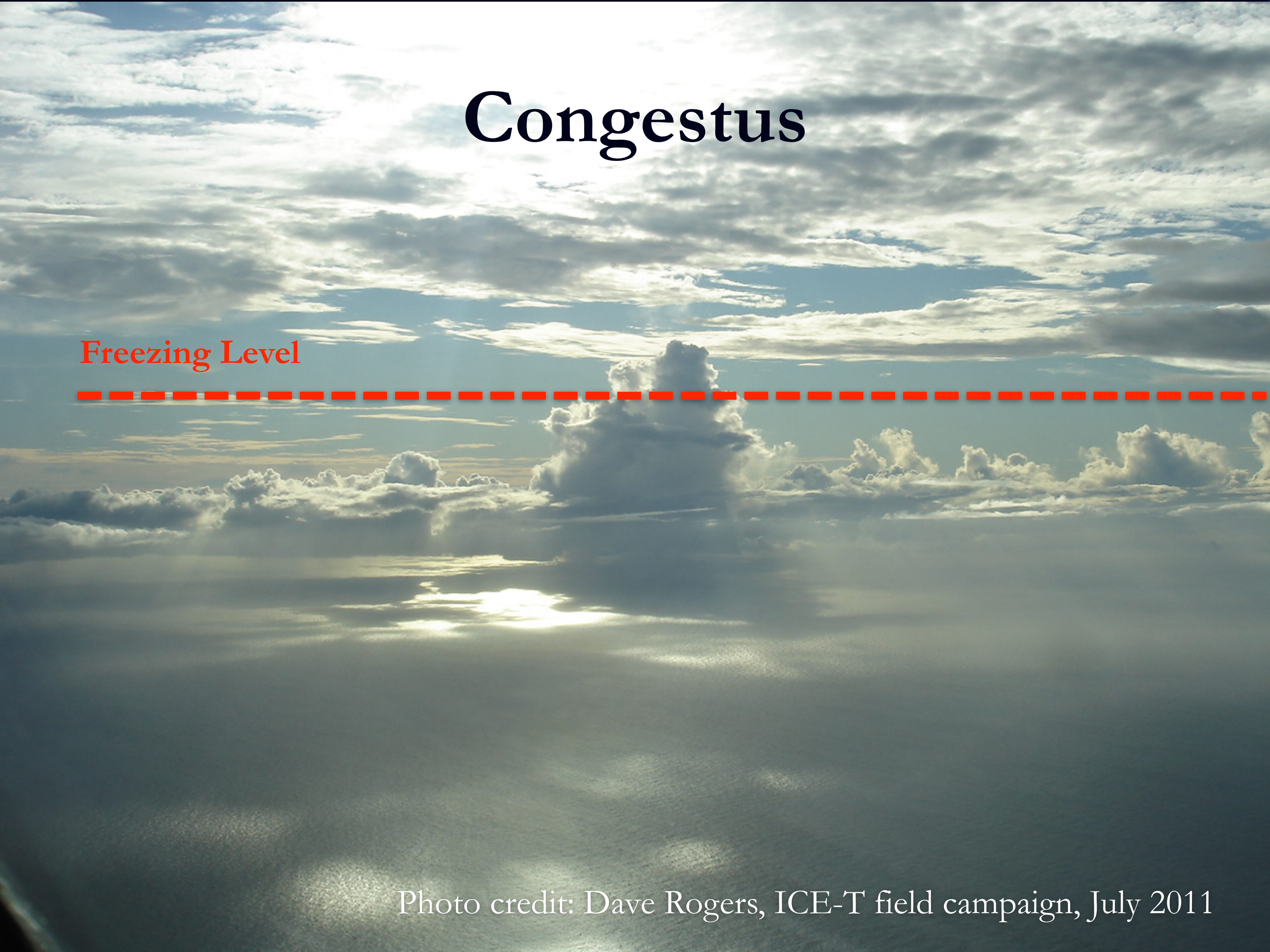
Trimodal Distribution

Deep Convective Mode
CTs~tropopause
Enhanced precipitation

Congestus Mode CTs~6km
Mixed response

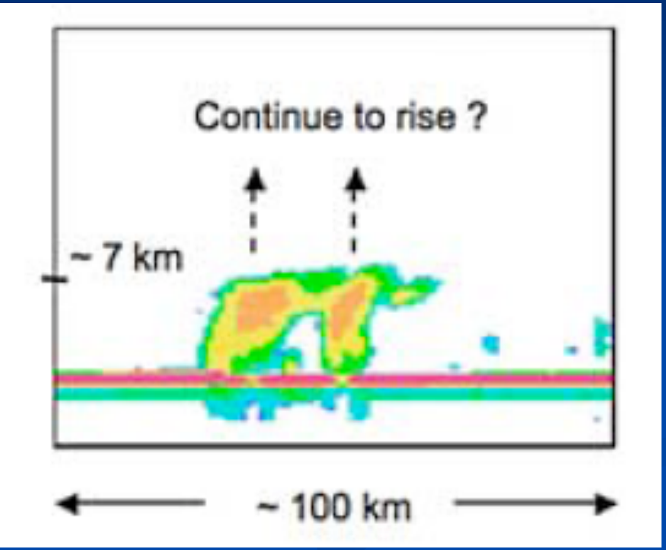
Shallow Convective Mode CTs~2km
Suppressed precipitation

Image Source: CRYSTAL-FACE website

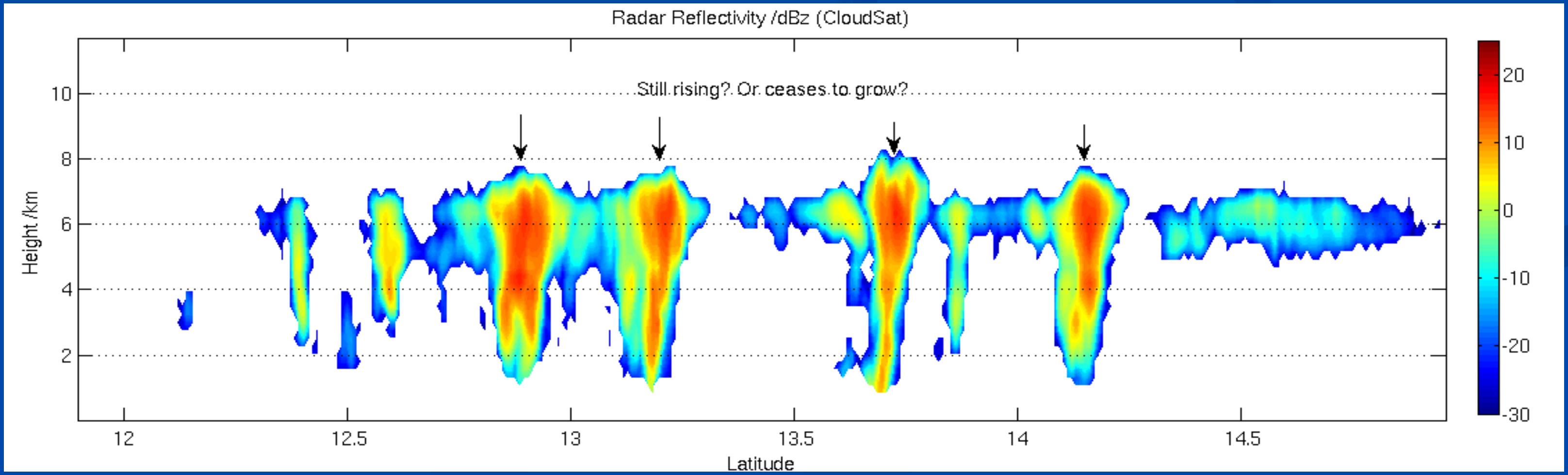

Congestus
Freezing Level
Photo credit: Dave Rogers, ICE-T field campaign, July 2011

Terminal versus Transient?

after Luo et al (2009) JGR



- Terminal versus transient congestus (Luo et al, 2009)
- Dynamical response to aerosol indirect forcing?

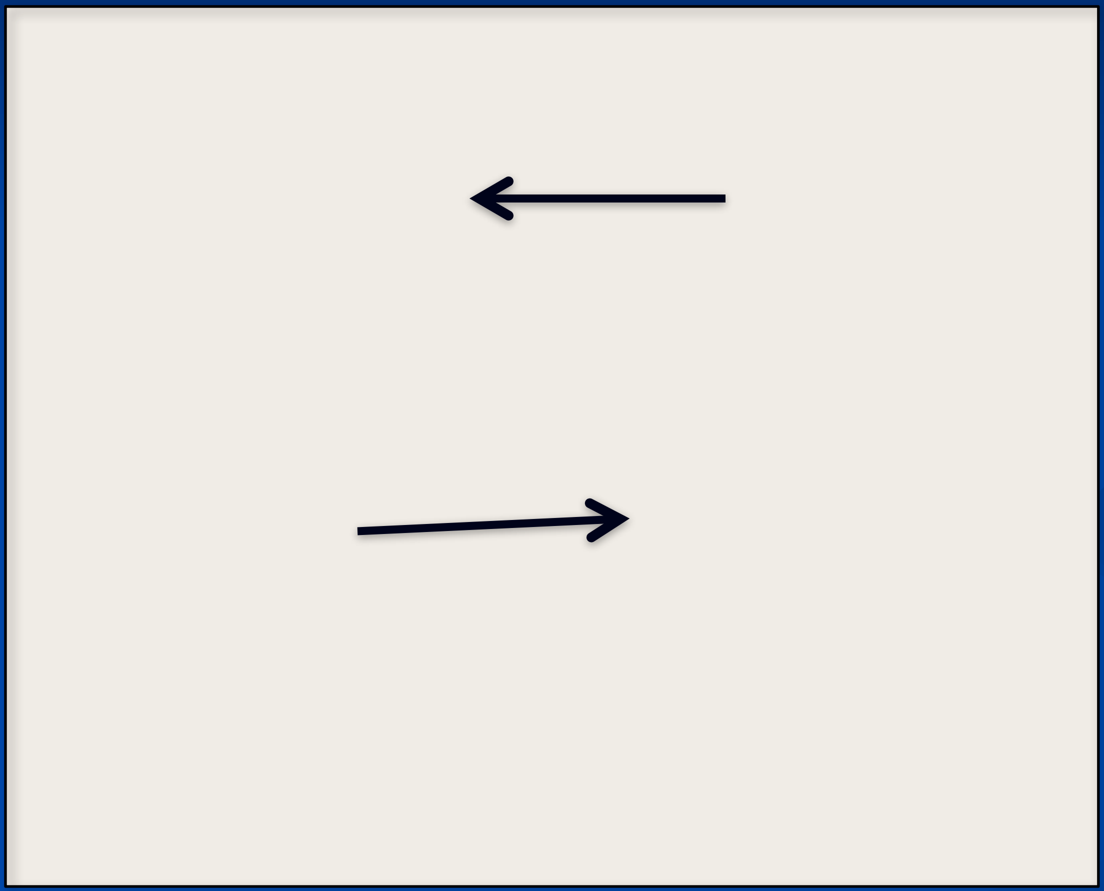


Congestus Cloud Top Frequency

- Higher CCN concentration => greater number of congestus clouds extending beyond the freezing level

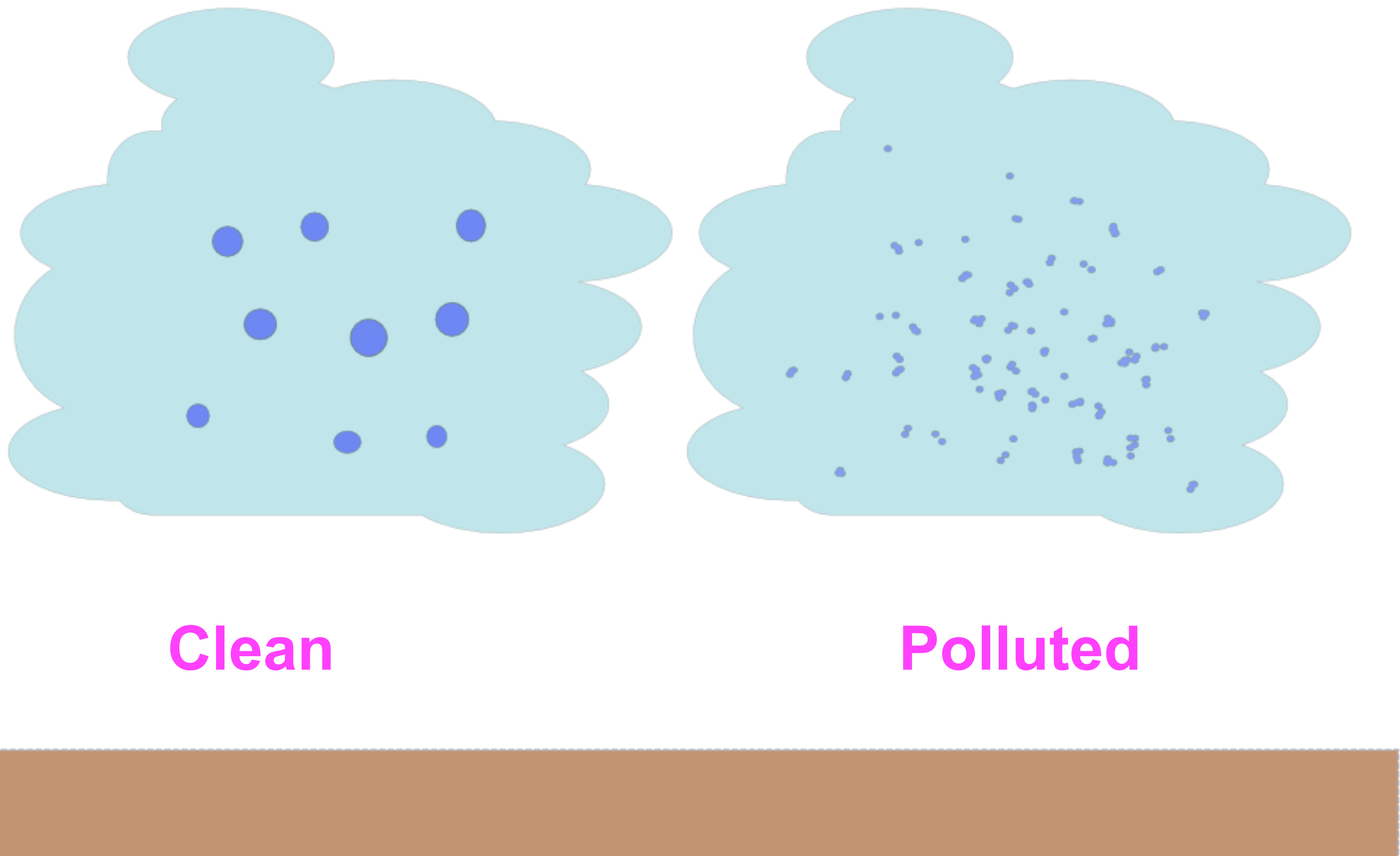
Histogram of congestus cloud top frequency as a function of aerosol concentration (Sheffield, van den Heever and Saleeby, 2012)

Cumulus Congestus Updraft Speeds



- Updraft speed generally increases in the more polluted cases, but this trend changes aloft

Greater net surface area enhances latent heat of condensation

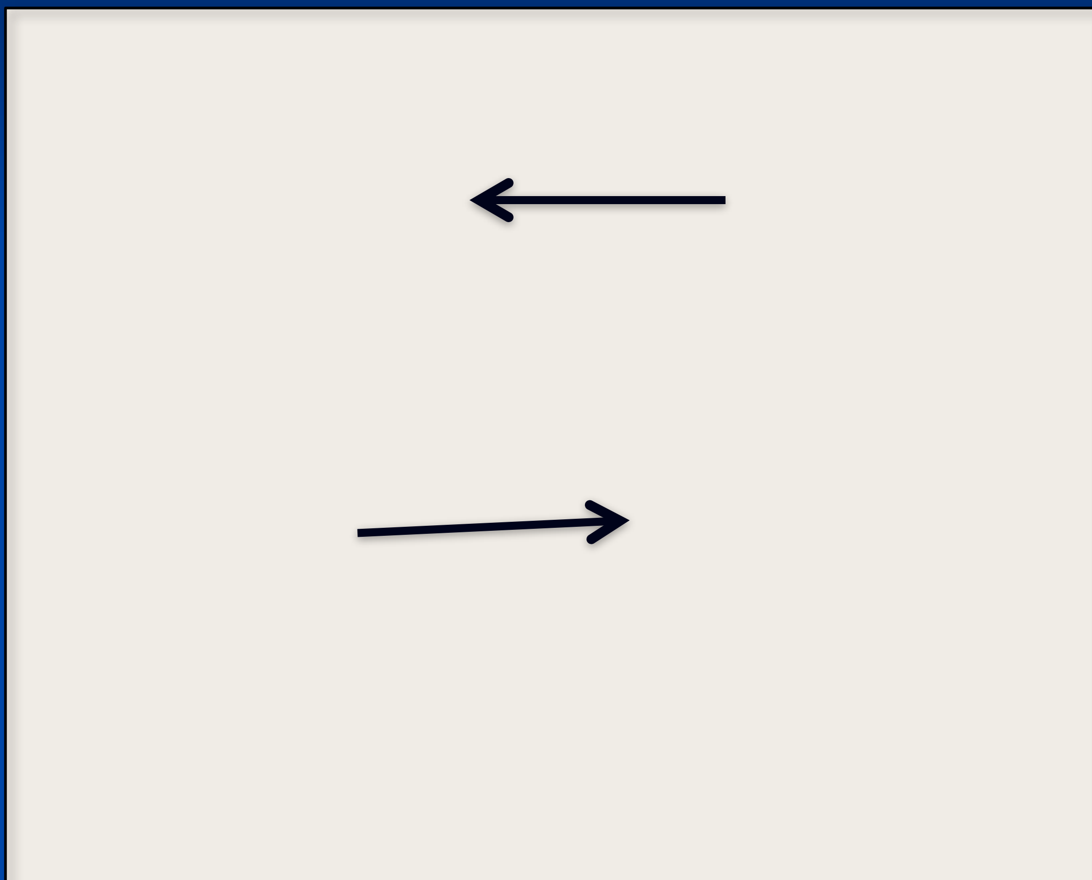


Latent Heat Release

Latent Heat of Vaporization

Latent Heat of Freezing

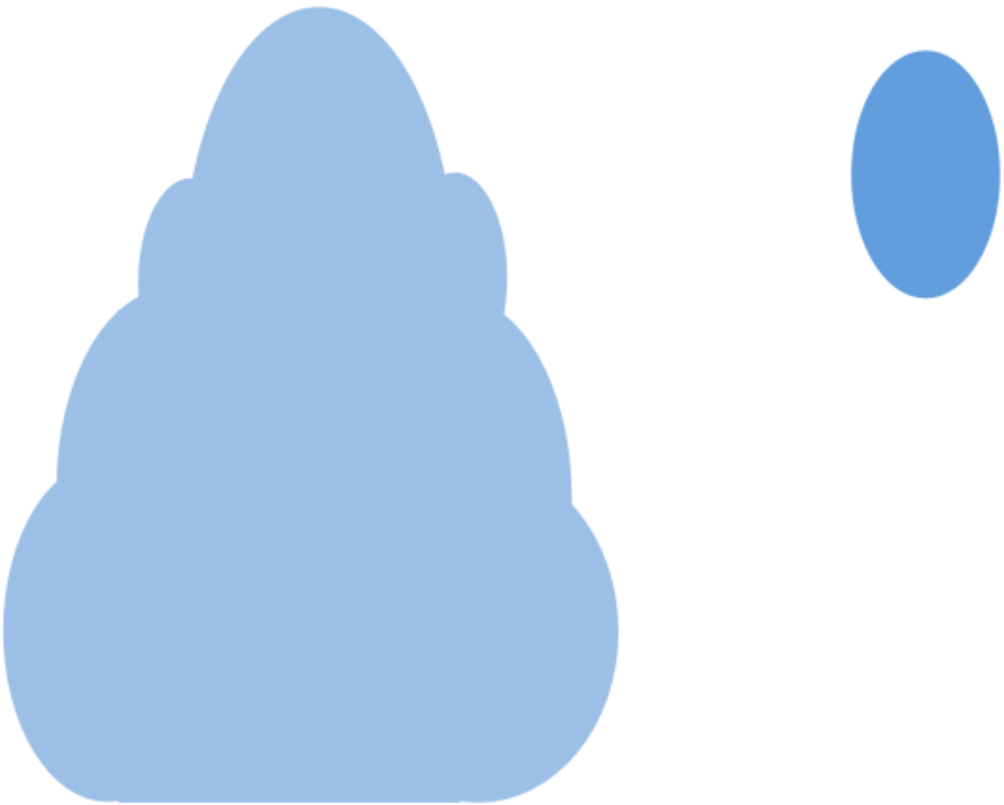
Cumulus Congestus Updraft Speeds



- Updraft speed generally increases in the more polluted cases, but this trend changes aloft

Condensate Loading

- Insufficient increased buoyancy due to ice formation to offset enhanced condensate loading



Congestus Summary

- Enhanced aerosol concentrations => invigorate congestus through condensational growth and associated latent heat release => produce greater frequency of congestus cloud tops above freezing level => enhanced opportunity for mixed-phase processes, further invigoration and development into deep convection