Aerosol Effects on Dynamics, Microphysics and Precipitation of Clouds and Cloud Systems: Physical Mechanisms and Classification

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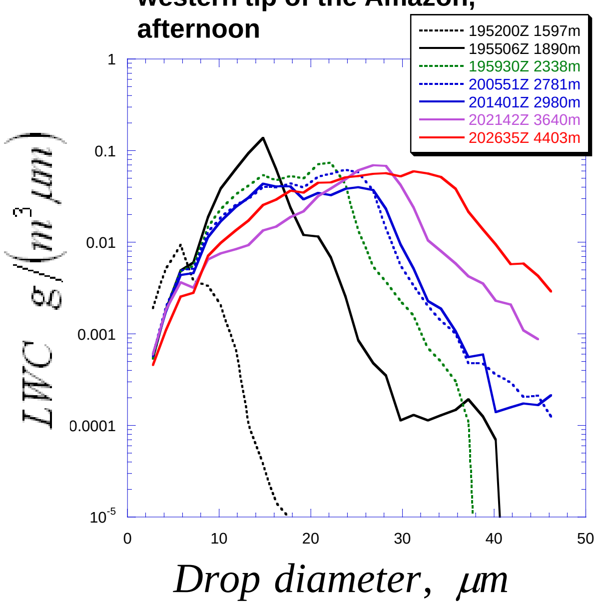
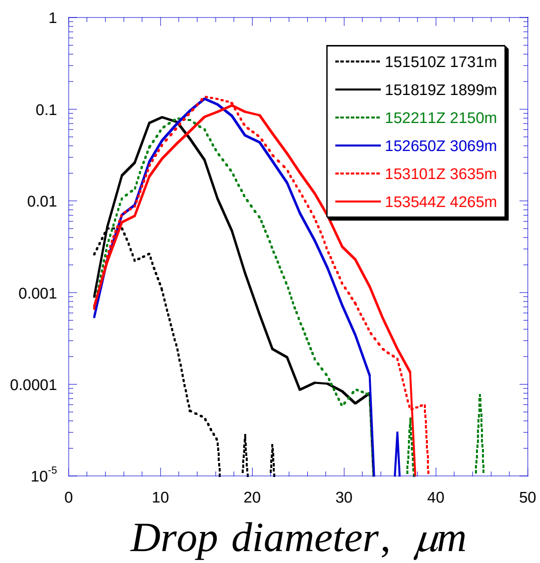
Droplet size distributions in growing cumulus clouds (LBA-SMOCC campaign 2002)

(*Andreae et al 2004-Science*)

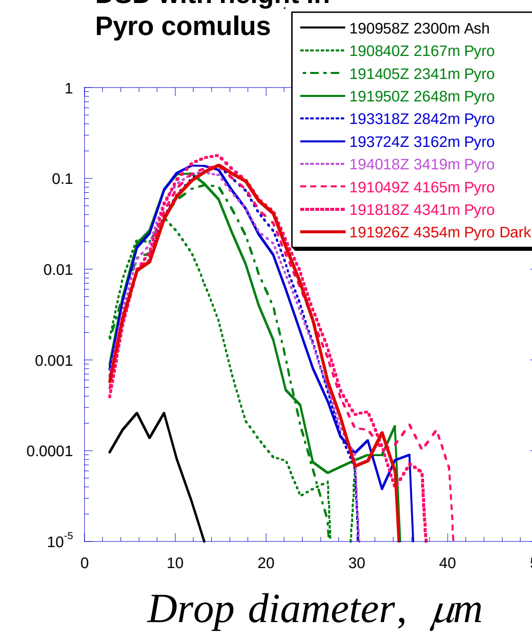
Warm rain evolution over the western tip of the Amazon, afternoon



Smoky conditions North of JPR, Noon

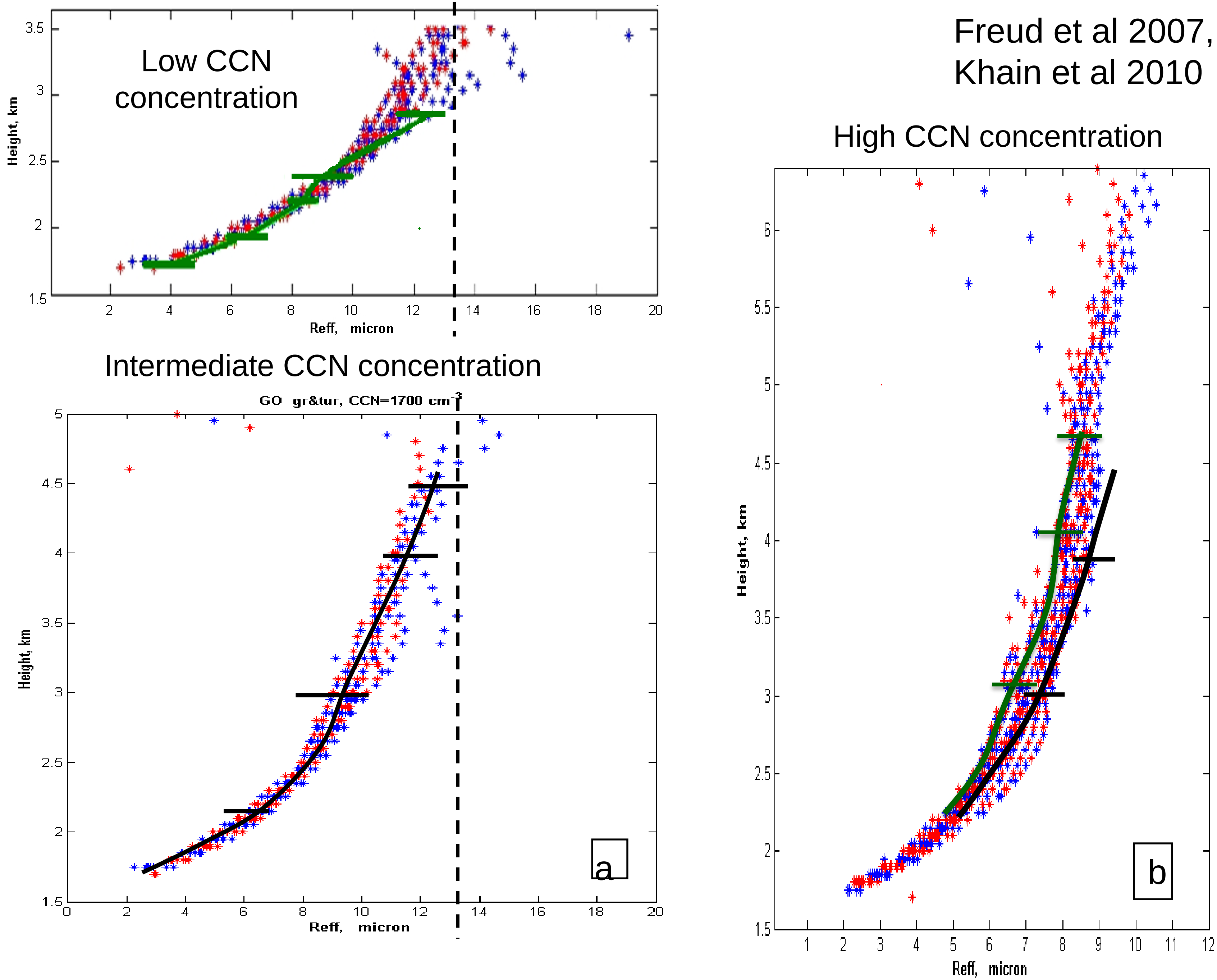


DSD with height in Pyro comulus



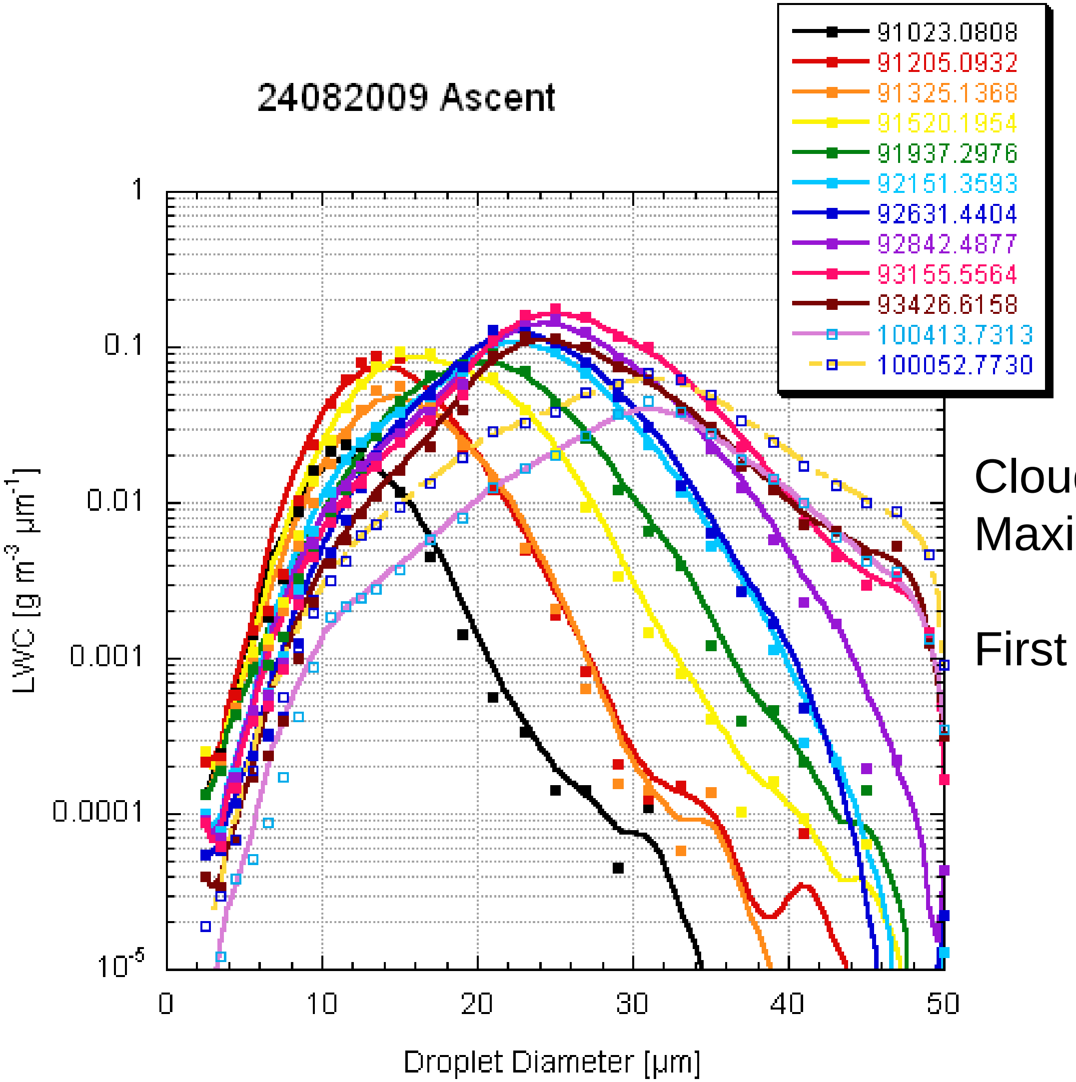
Reff (z) Amazon region, LBA-SMOCC 2002

Freud et al 2007,
Khain et al 2010



SIZE DISTRIBUTIONS IN DEEP CONVECTIVE CLOUD OVER INDIA DURING MONSOON PERIOD (24 Aug 2009)

CCN CONCENTRATION (at 1% S) =10000 cm-3 (!!!)



Cloud base: 800 m

Maximum CWC 5 g/m3

First raindrops at z=5.5 km (!)

Aerosol effects on precipitation

Aerosols inhibit precipitation:

Kaufman and Nakajima 1993;

Borys et al, 1998; 2000;

Rosenfeld and Lensky 1998;

Rosenfeld 1999, 2000;

Givati and Rosenfeld 2004

Tao et al (1995), Ferrier et al (1996

Khain et al, 2001;

Khain and Pokrovsky (2004);

Khain et al (2004a,b)

Axel et al (2004);

Tao et al (2004)

Teller and Levin(2006)

Margaritz et al (2007)

Lynn et al (2006)
Lin et al (2006)

Jirak and Cotton (2006)

Tao et al (2007)

Khain and Lynn (2007)

Fan et al (2010)

Storer wt al (2010)

Aerosols can increase precipitation:

Ohashi and Kida 2002

Shepherd and Burian 2003

Amiranashvili et al 2004

Filho et al (2004)

Khain et al (2004a,b)

Khain et al (2005-QJRMS)

Axel et al (2004);

Axel and Beheng (2004)

Tao et al (2004, 2007)

Van den Heever et al (2004)

Lynn et al (2005a,b)

Wang (2005)

Lynn et al (2006)

Khain et al (2005, 2006, 2007)

Khain and Pokrovsky (2006)

Tao et al (2007)

Khain and Lynn (2007)

Li et al 2006

Lee et al 2005, 2008

Precipitation

Precip = **GAIN** **-** **LOSS**

(condensation+ ice deposition) (evaporation+ ice sublimation)

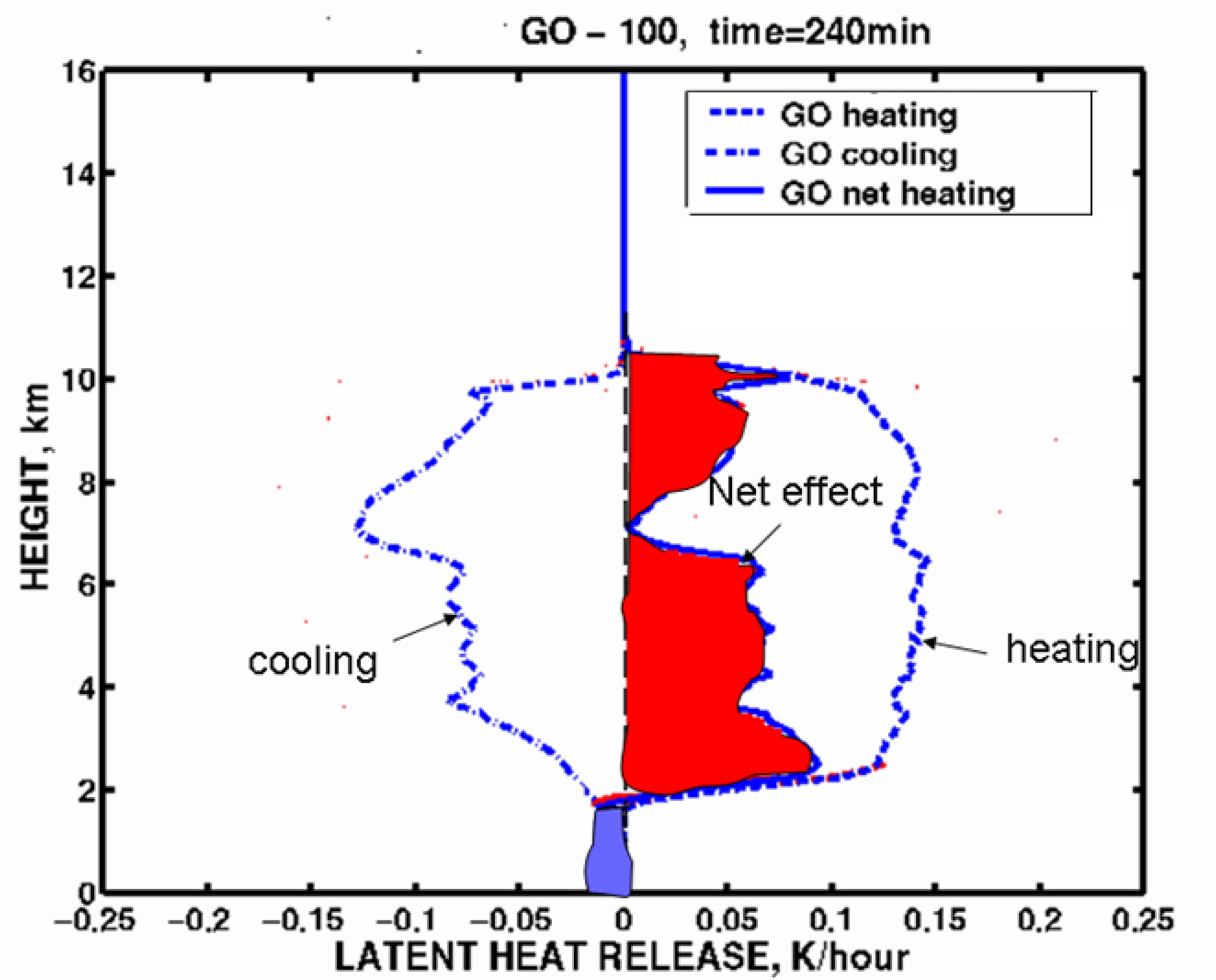
Precipitation is often a small difference of large values

Aerosols affect both generation and loss of hydrometeor mass

Δ Precip = **Δ GAIN** **-** **Δ LOSS**

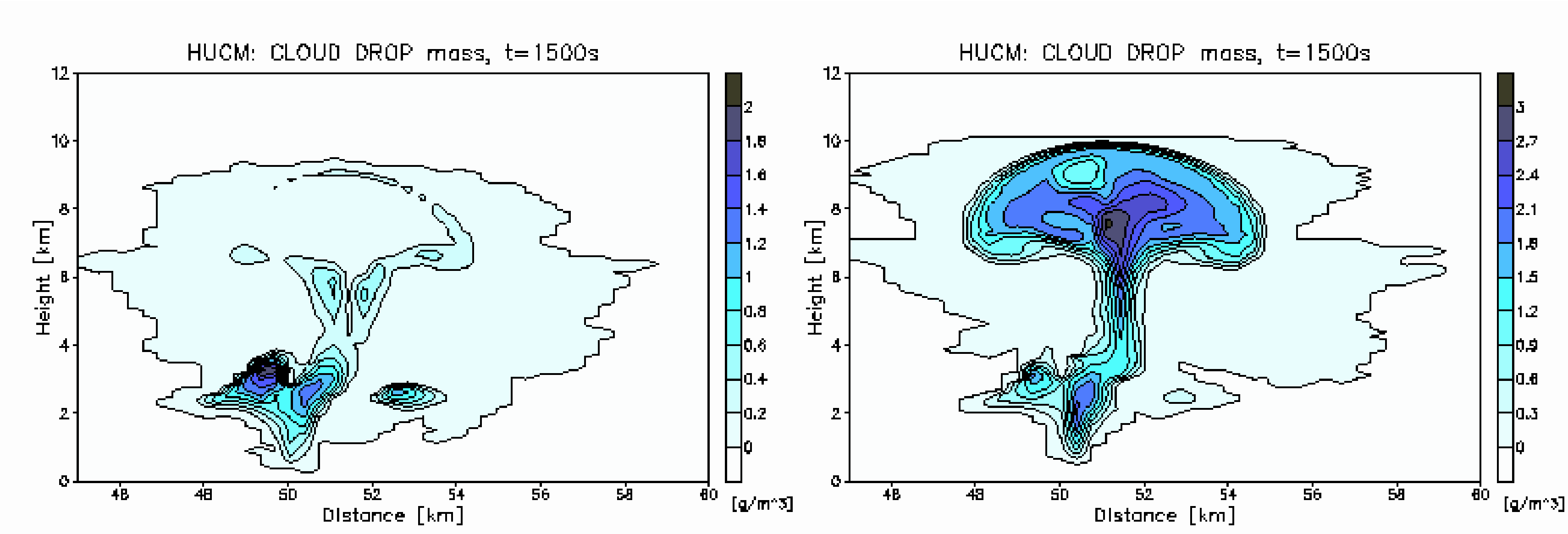
Heat budget in green-ocean (clean) clouds over Amazon as simulated using the Hebrew University cloud model (HUCM), Khain et al, JAS 2008)

Effect of clouds on atmospheric heating/cooling



CONVECTIVE INVOGORATION

LOW CCN concentration | HIGH CCN concentration

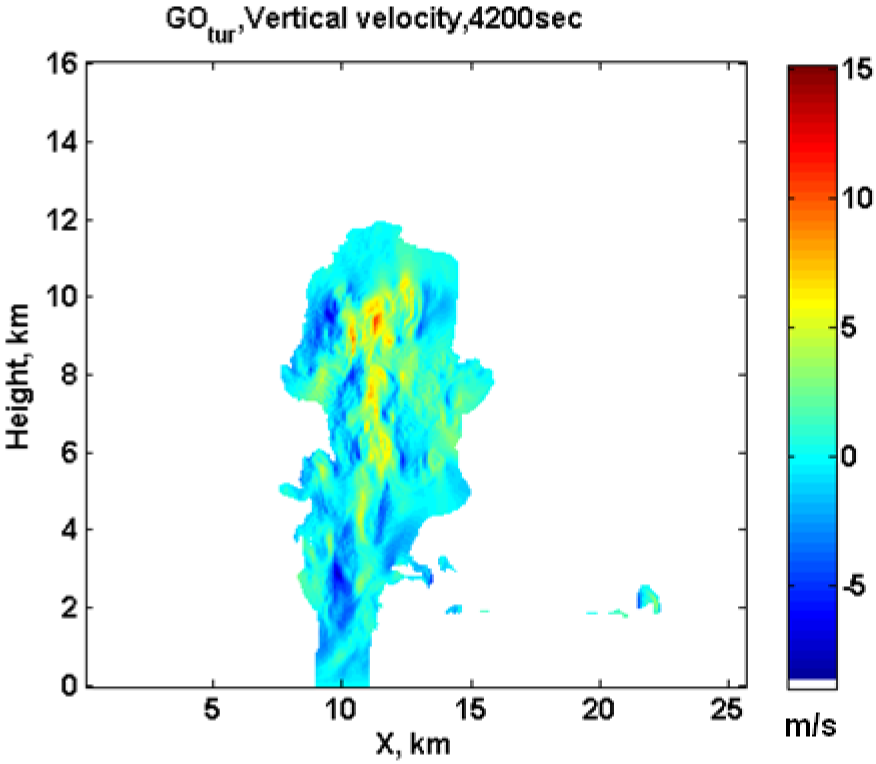


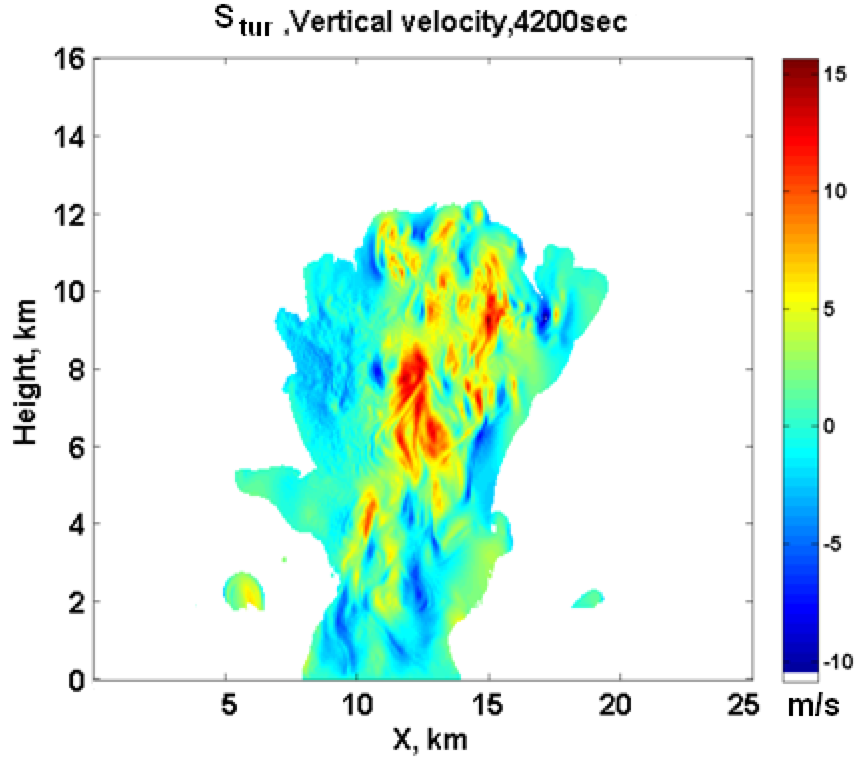
Khain et al 2008, JAS

CONVECTION INVIGORATION

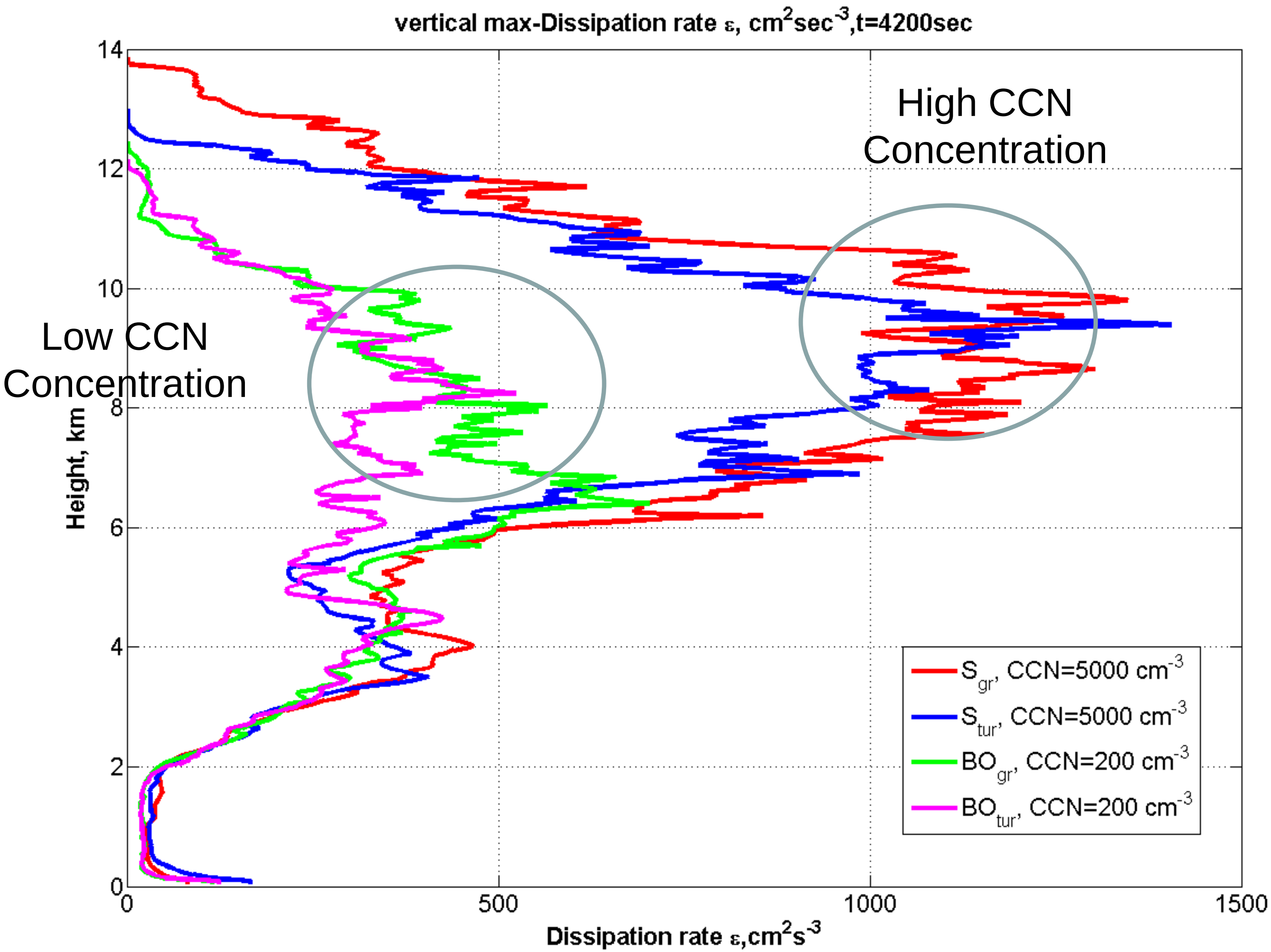
Low CCN concentration

High CCN concentration

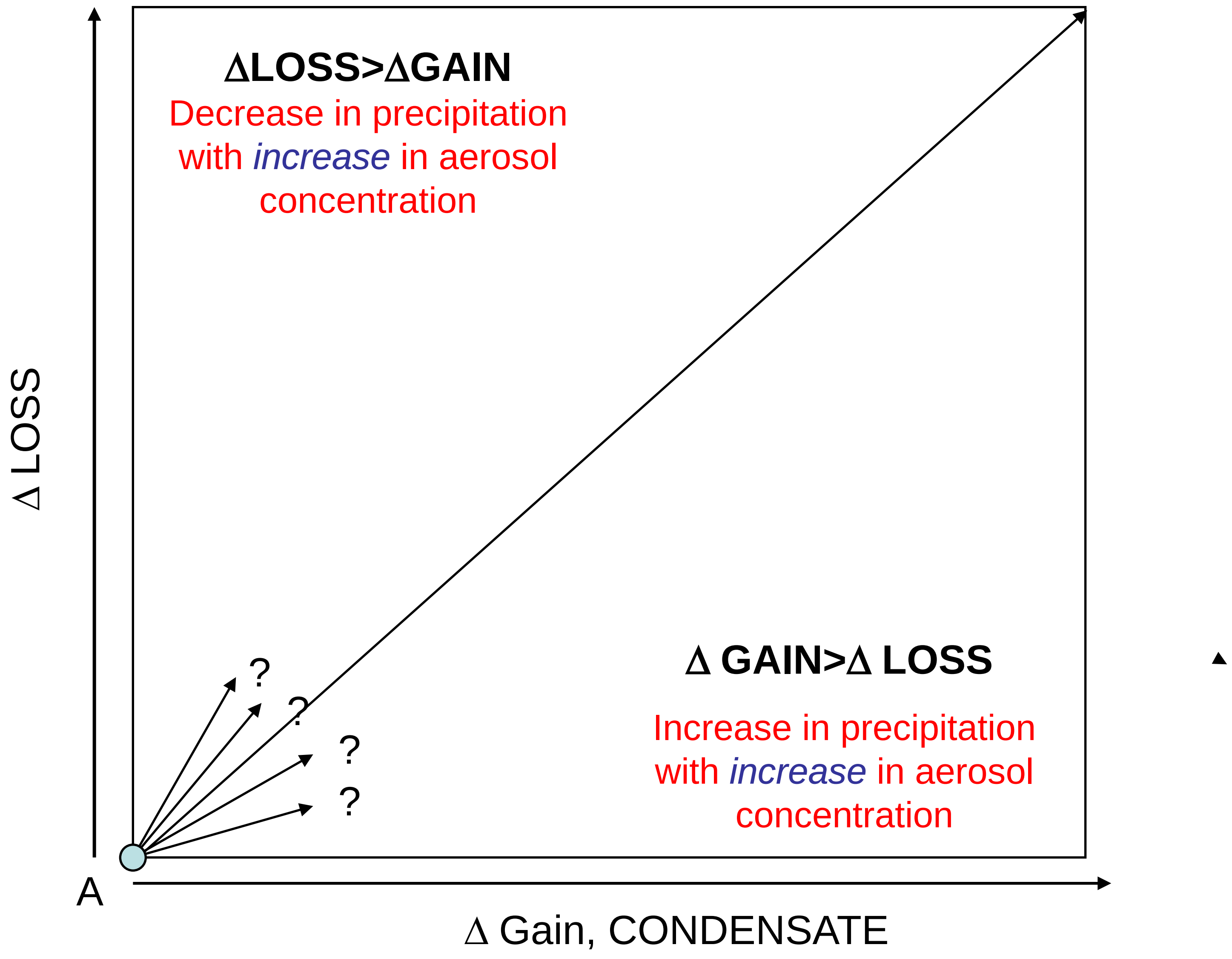




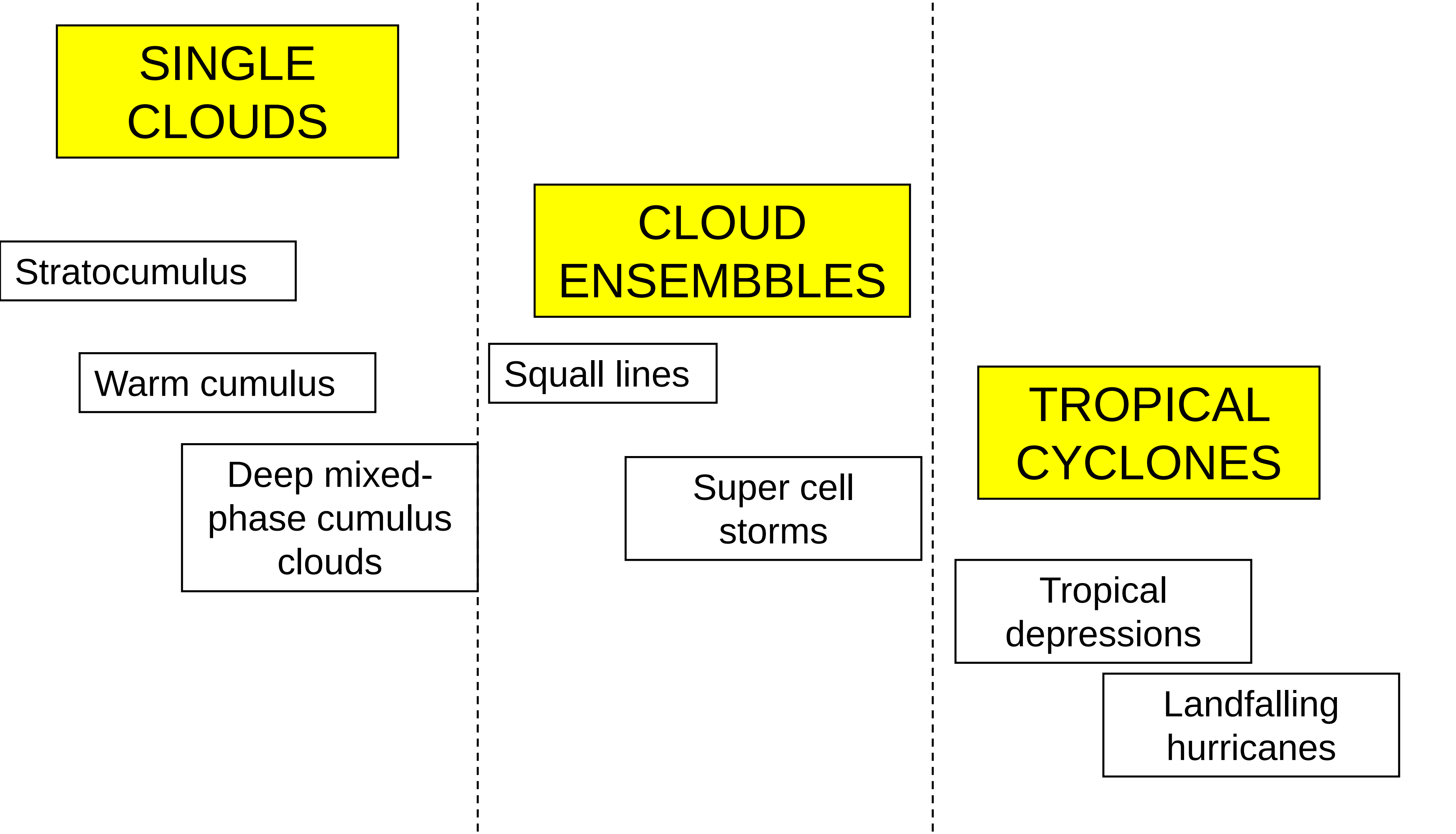
TURBULENT STRUCTURE OF POLLUTED AND CLEAN CONVECTIVE CLOUDS



Possible scenarios of aerosol effects on precipitation



Aerosols affect microphysics and dynamics of clouds and cloud systems
but possibly via different physical mechanisms



SINGLE CLOUDS

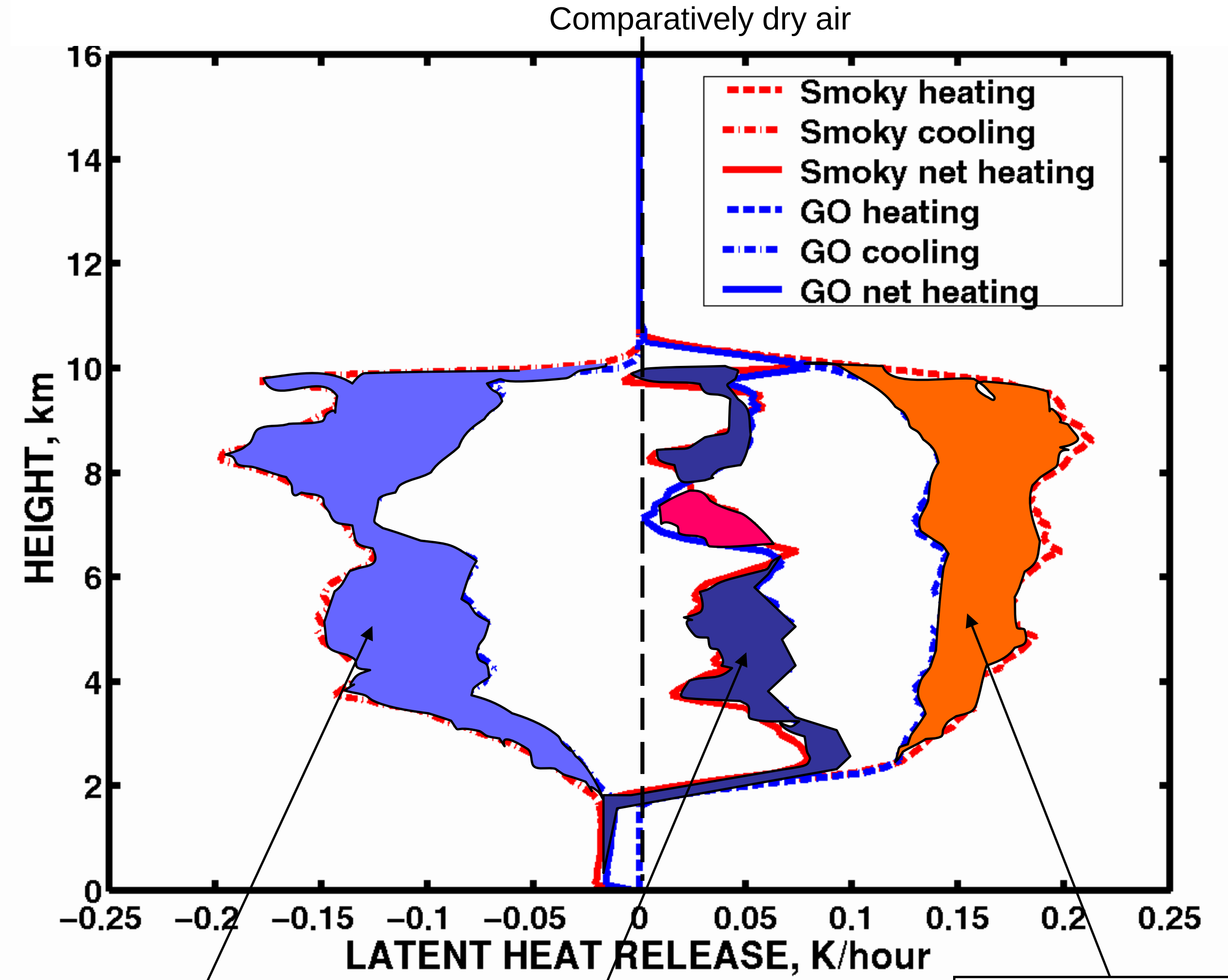
Main environmental factors:

Air humidity

Wind shear

Khain et al 2008, JAS

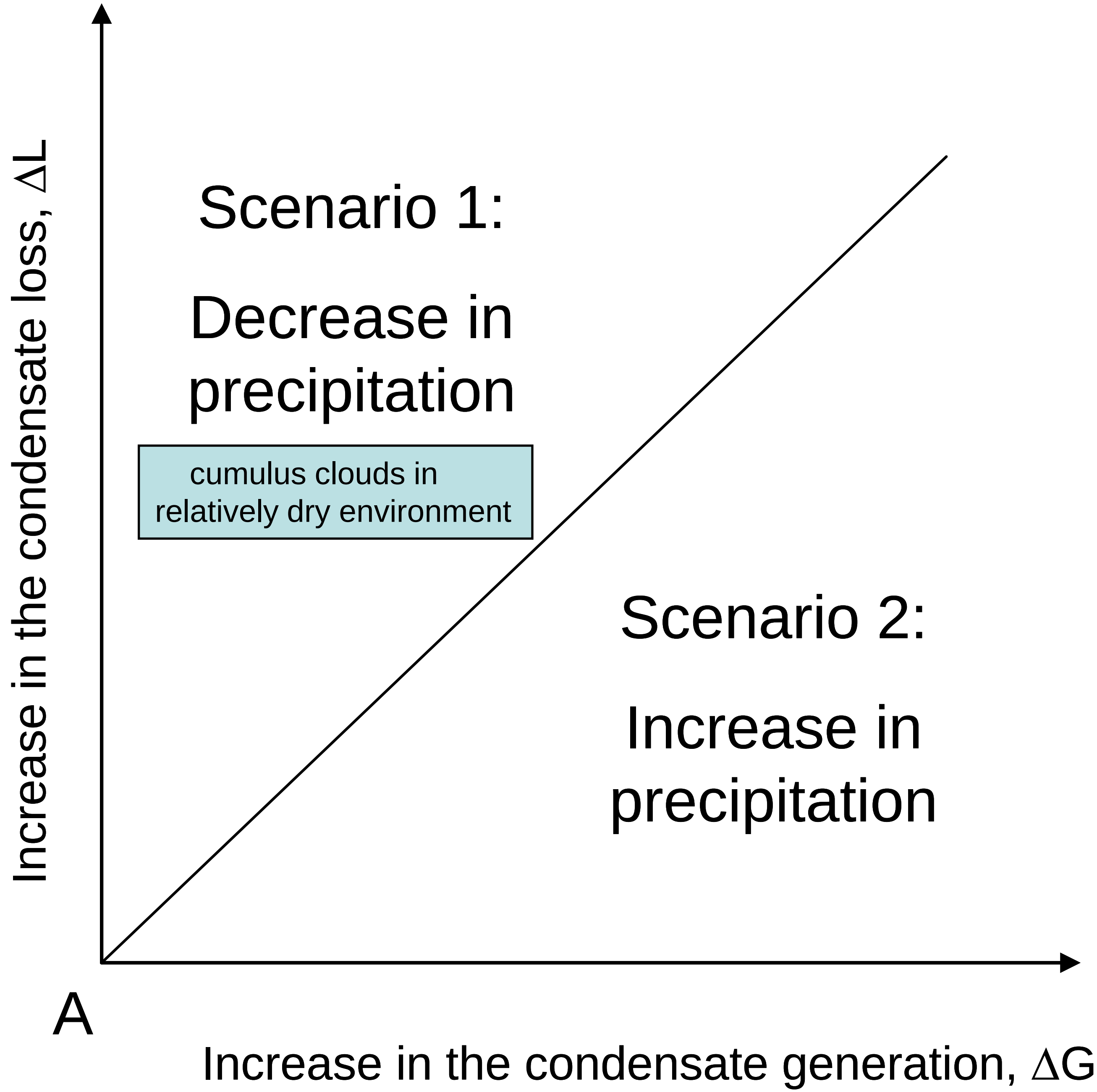
Smoky and Green-Ocean Clouds (SMOCC campaign), t=240 min

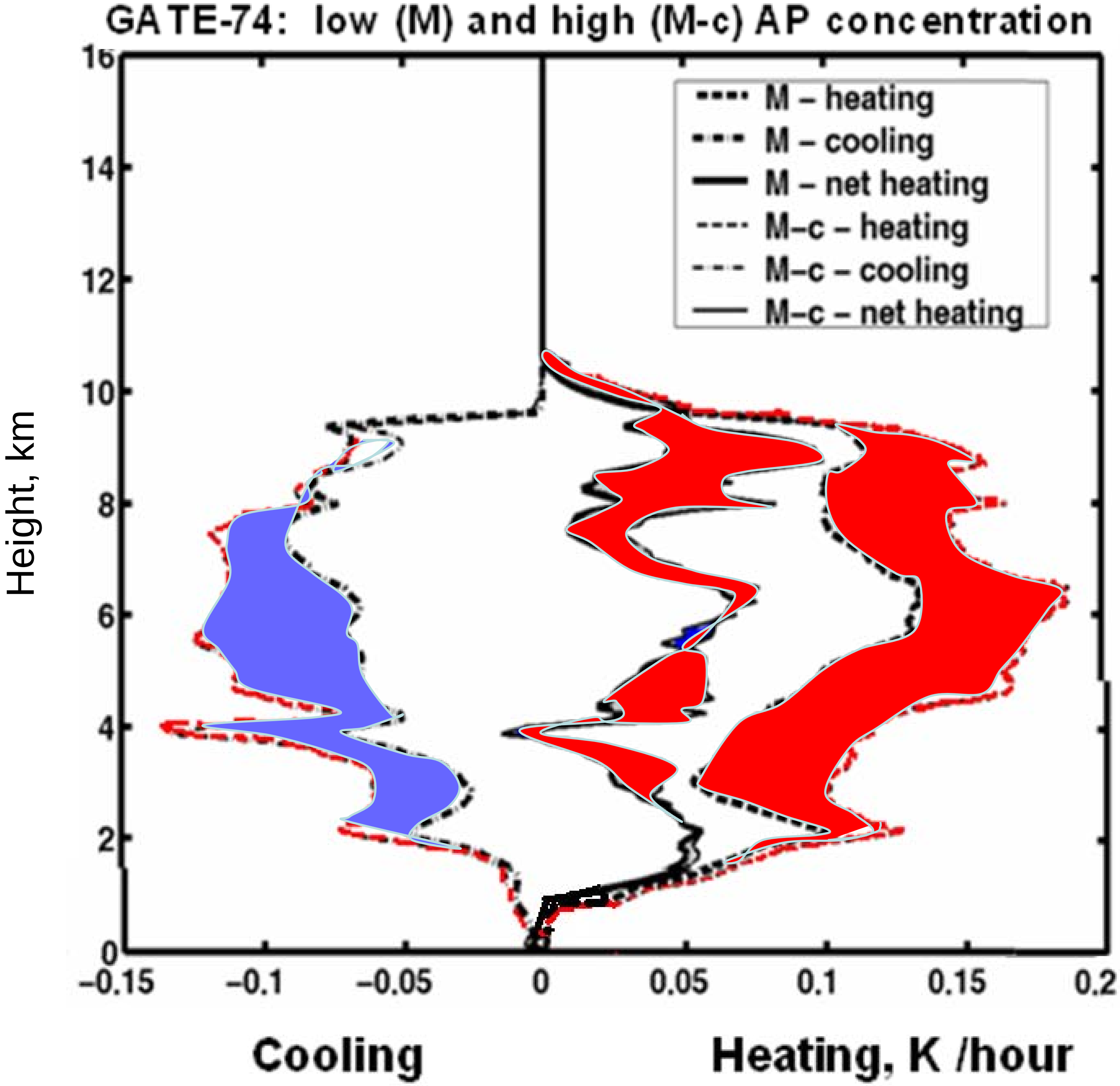


Cooling in polluted clouds is larger

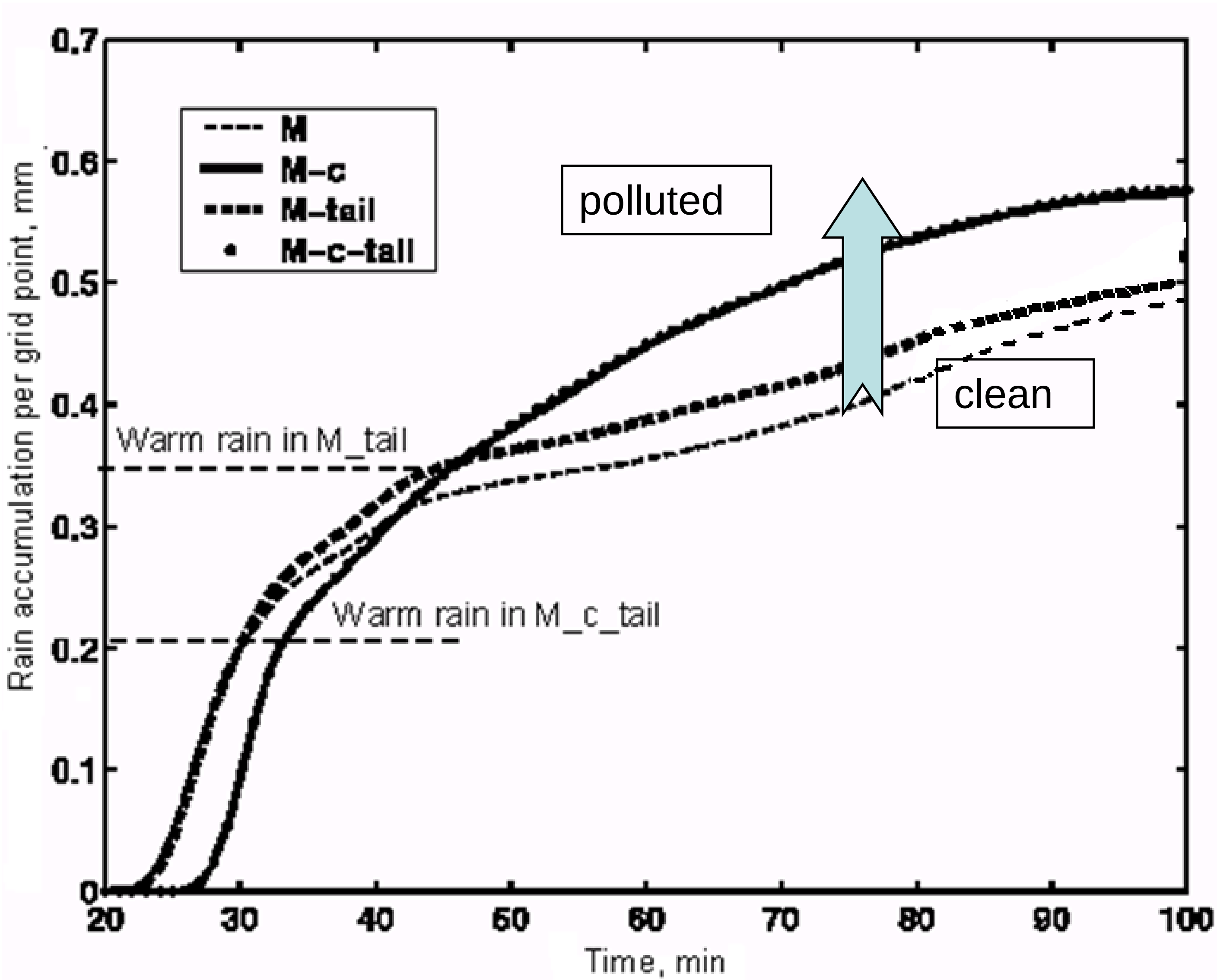
Net effect: heating (=precipitation) is larger in clean air cloud

Heating in polluted clouds is larger

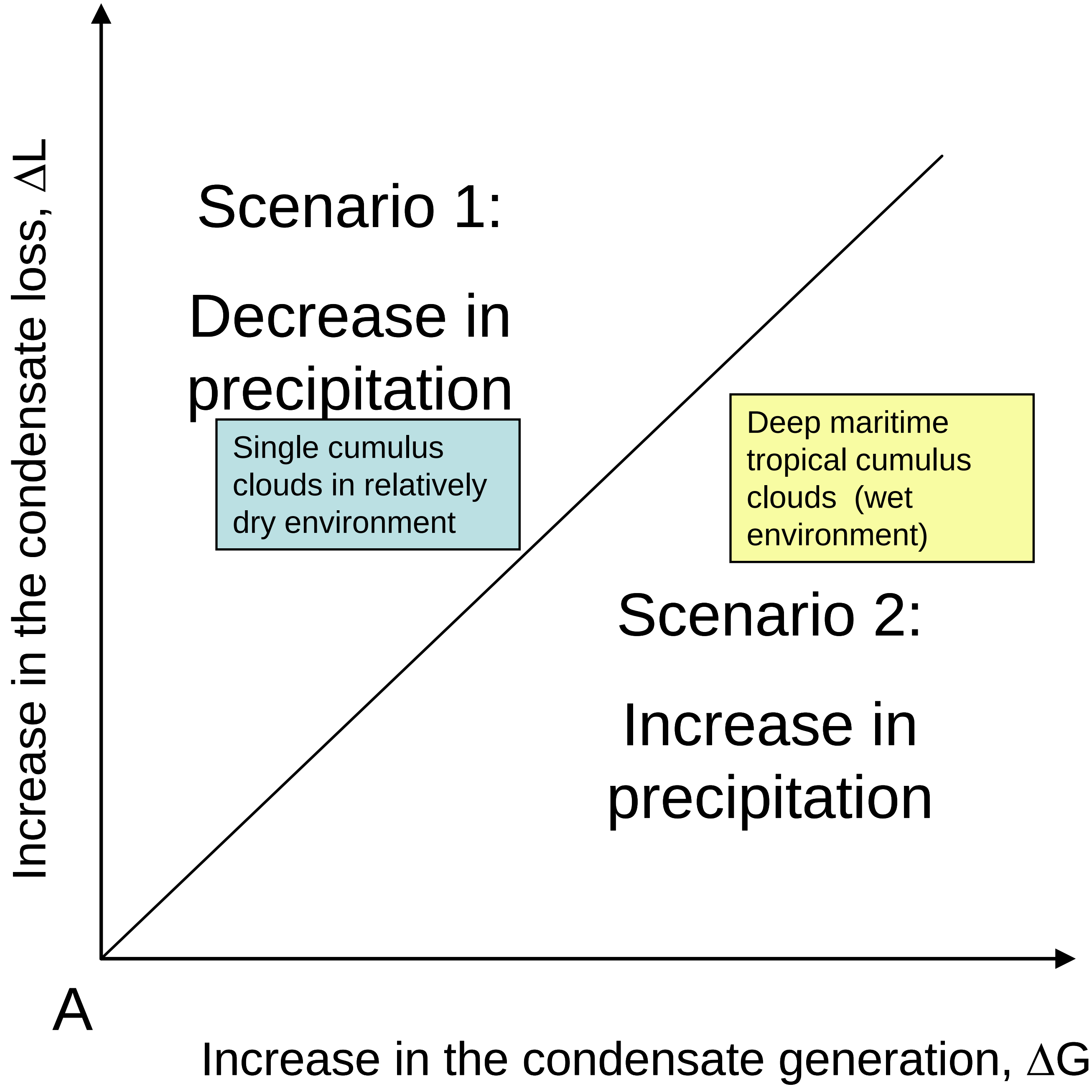

Increase in the condensate loss, ΔL
Scenario 1:
Decrease in precipitation
cumulus clouds in relatively dry environment
Scenario 2:
Increase in precipitation
A
Increase in the condensate generation, ΔG



GATE-74: low (M) and high (M-c) AP concentration
M – heating
M – cooling
M – net heating
M–c – heating
M–c – cooling
M–c – net heating
Height, km
16
14
12
10
8
6
4
2
0
–0.15
–0.1
–0.05
0
0.05
0.1
0.15
0.2
Cooling
Heating, K /hour



M
M-c
M-tail
M-c-tail
polluted
clean
Warm rain in M_tail
Warm rain in M_c_tail
Rain accumulation per grid point, mm
Time, min
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
30
40
50
60
70
80
90
100


Increase in the condensate loss, ΔL
Scenario 1:
Decrease in precipitation
Single cumulus clouds in relatively dry environment
Deep maritime tropical cumulus clouds (wet environment)
Scenario 2:
Increase in precipitation
A
Increase in the condensate generation, ΔG

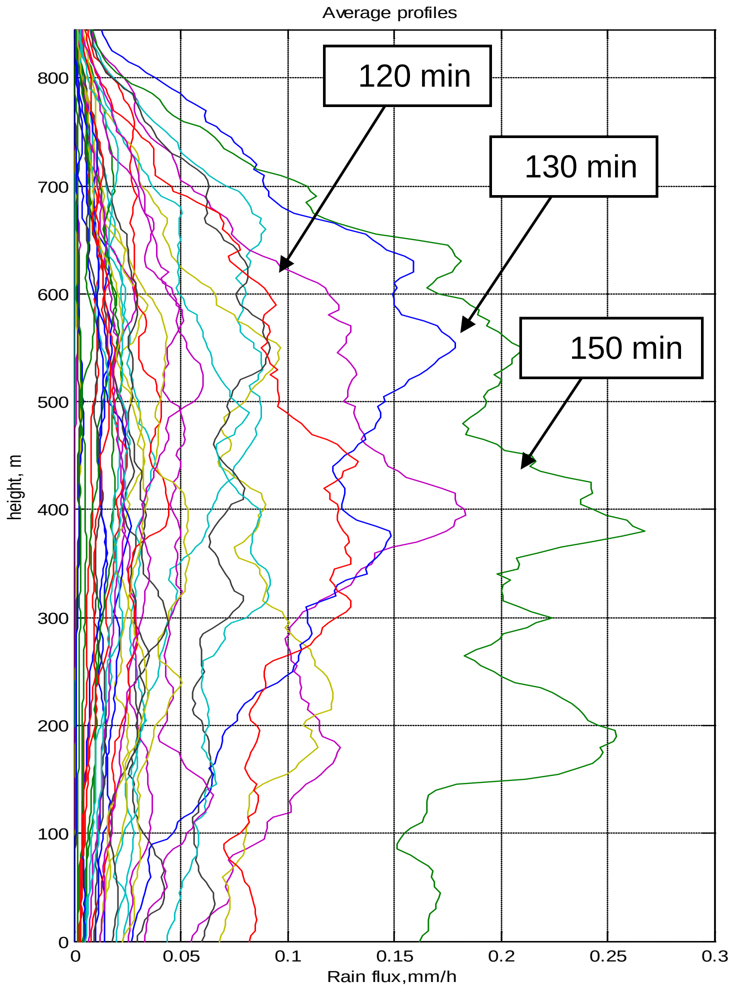
Stratocumulus and small cumulus clouds

ΔLoss>ΔGain

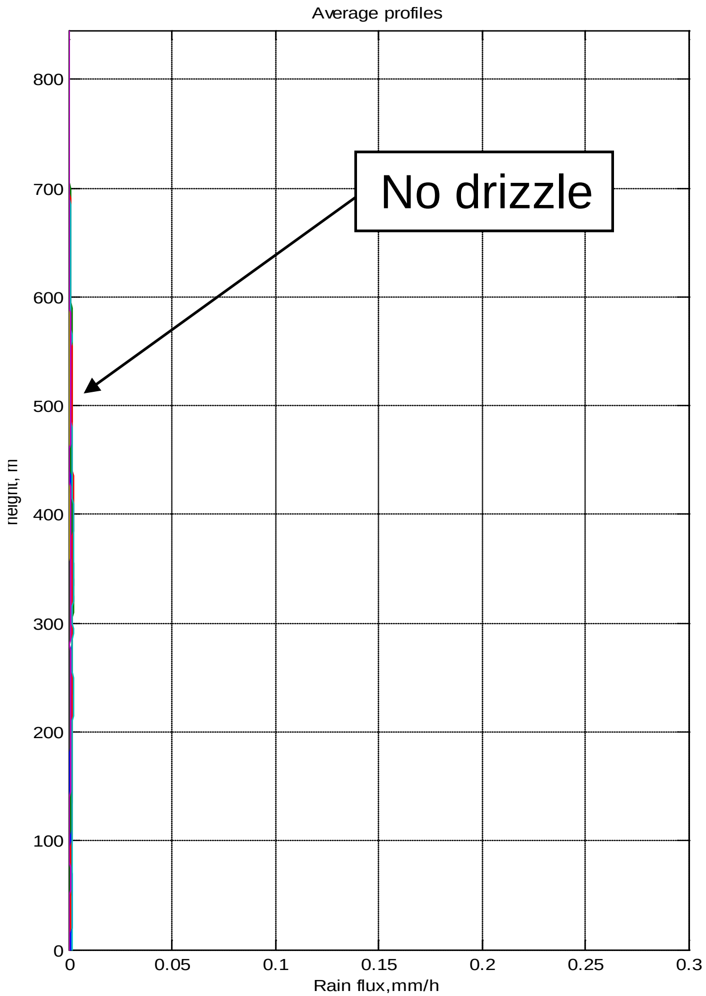
Vertical profiles of rain flux (drizzle)

Simulation of flight 2, DYCOMS-II ,

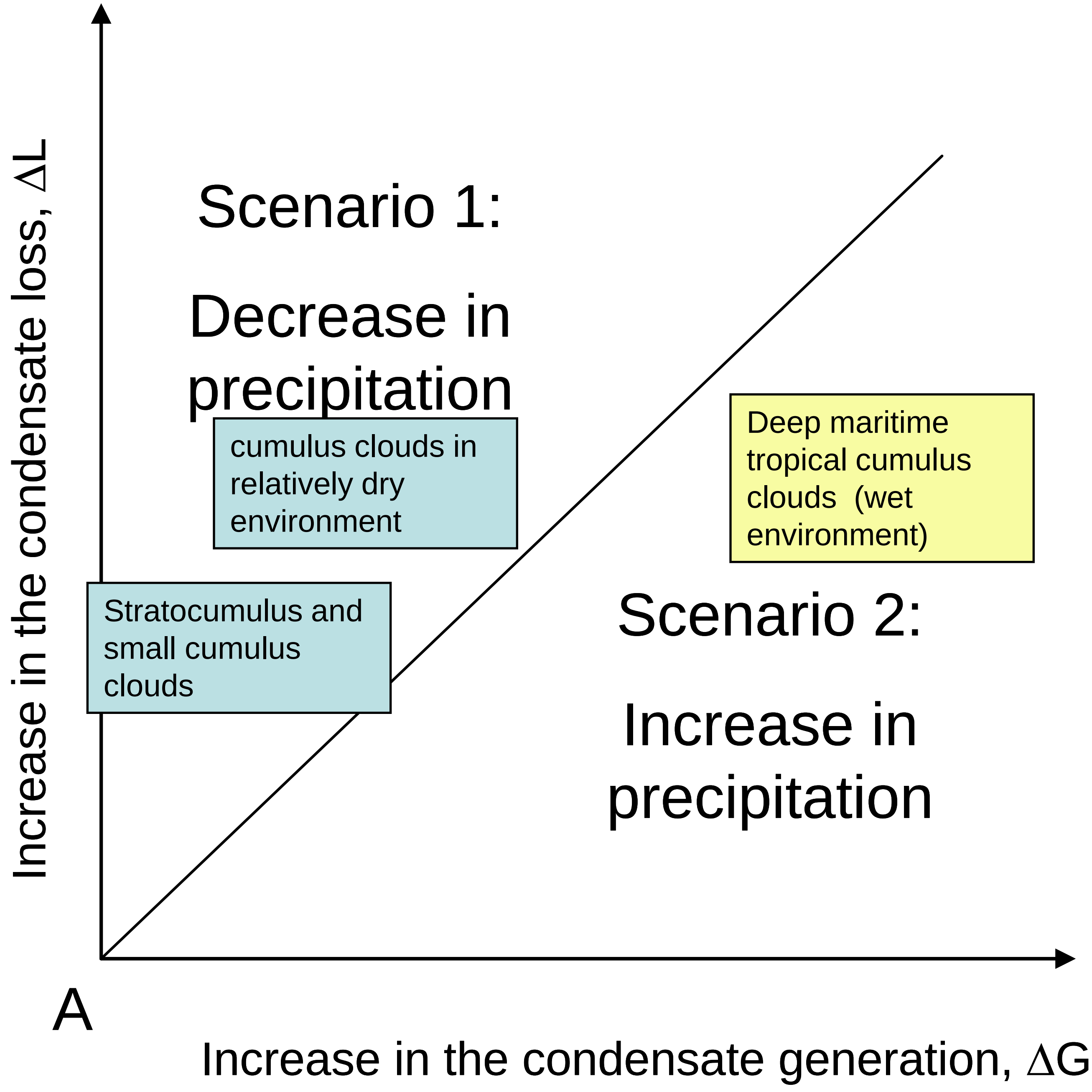
~200 CCN cm^{-3}



Increased (x3) concentration of aerosols



Pinsky, Khain and Magaritz (2007)

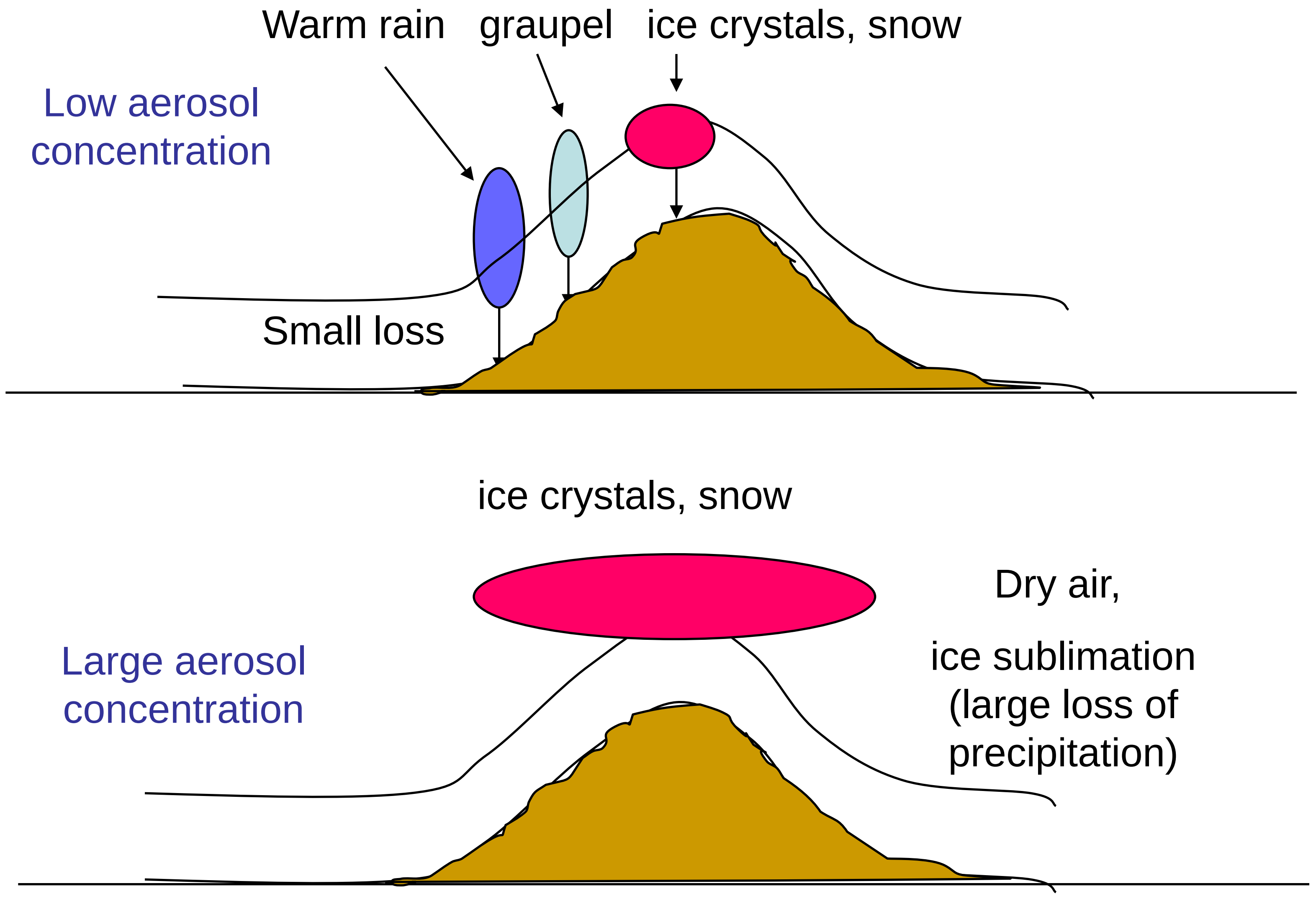


Scenario 1:
Decrease in precipitation
cumulus clouds in relatively dry environment
Stratocumulus and small cumulus clouds
Deep maritime tropical cumulus clouds (wet environment)
Scenario 2:
Increase in precipitation
Increase in the condensate loss, ΔL
A
Increase in the condensate generation, ΔG

Orographic clouds

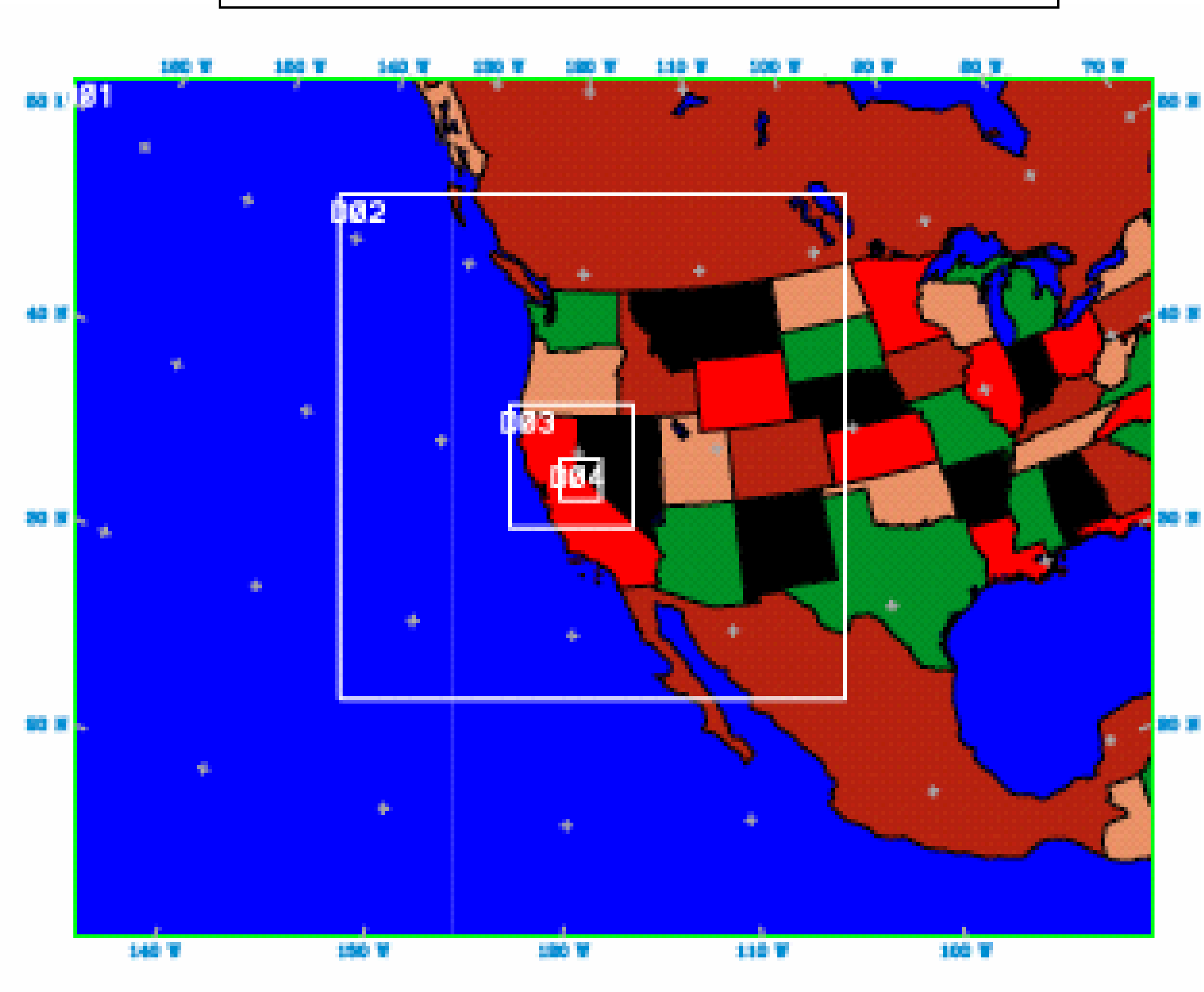
Δ Loss>Δ Gain

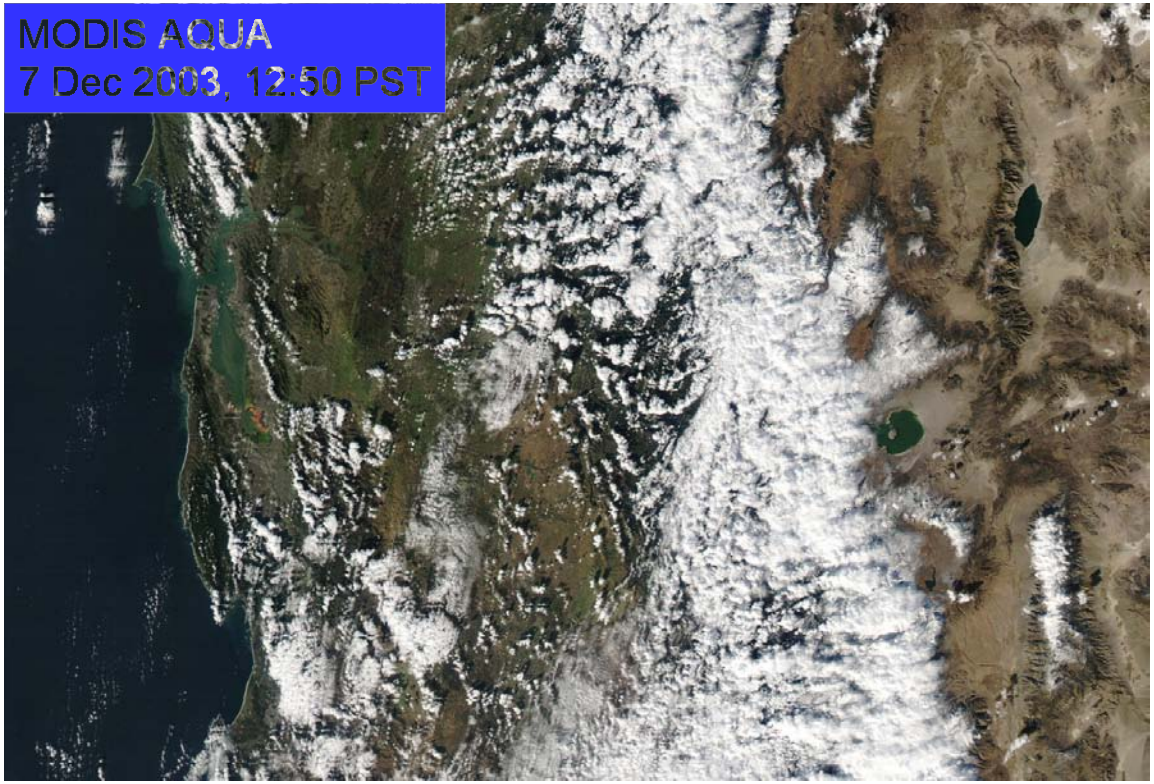
Aerosol effects on precipitation from orographic clouds



Khain et al 2007

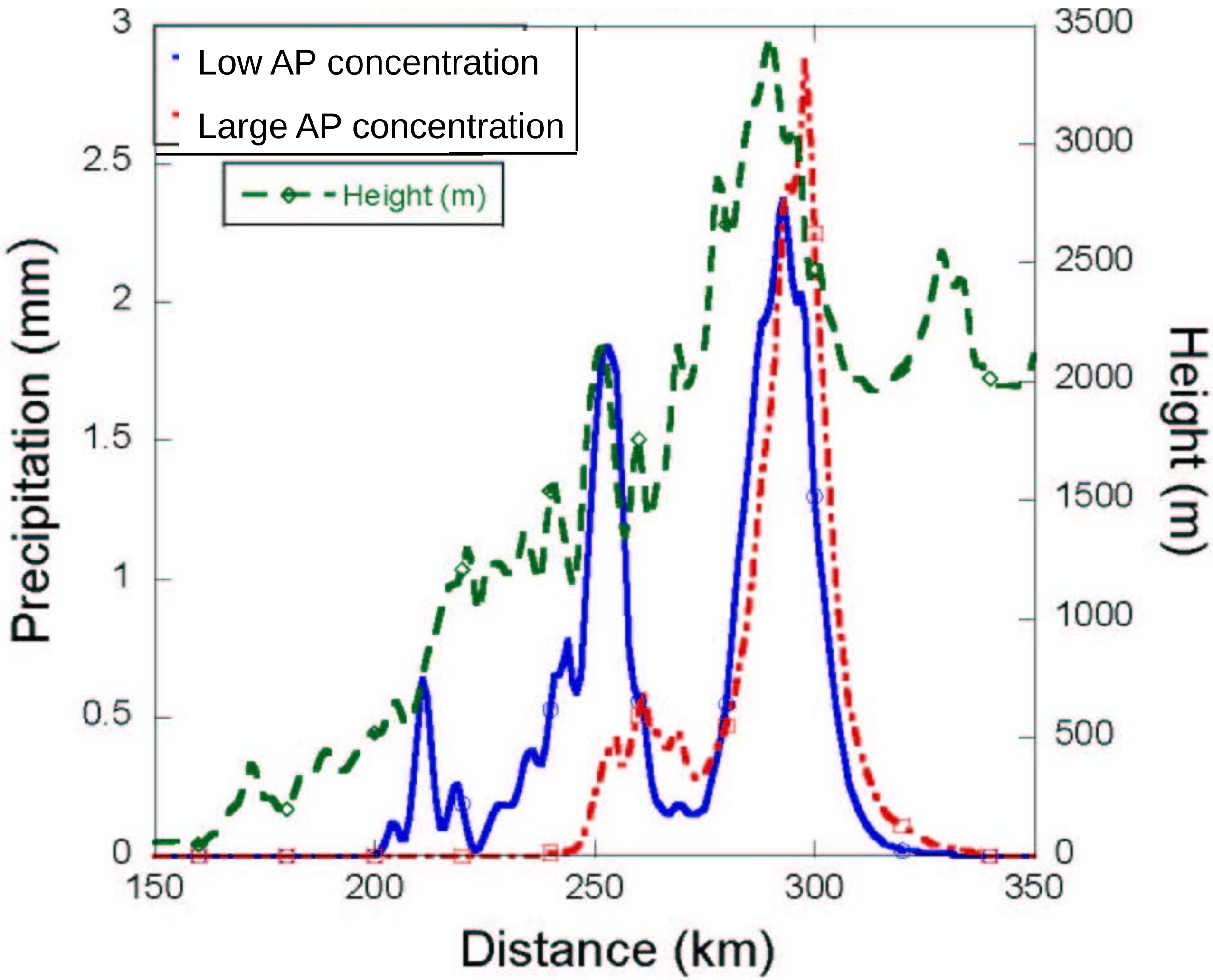
MM5 model with spectral (bin) microphysics




MODIS AQUA
7 Dec 2003, 12:50 PST

Accumulated rain calculated using 2D WRF model with SBM

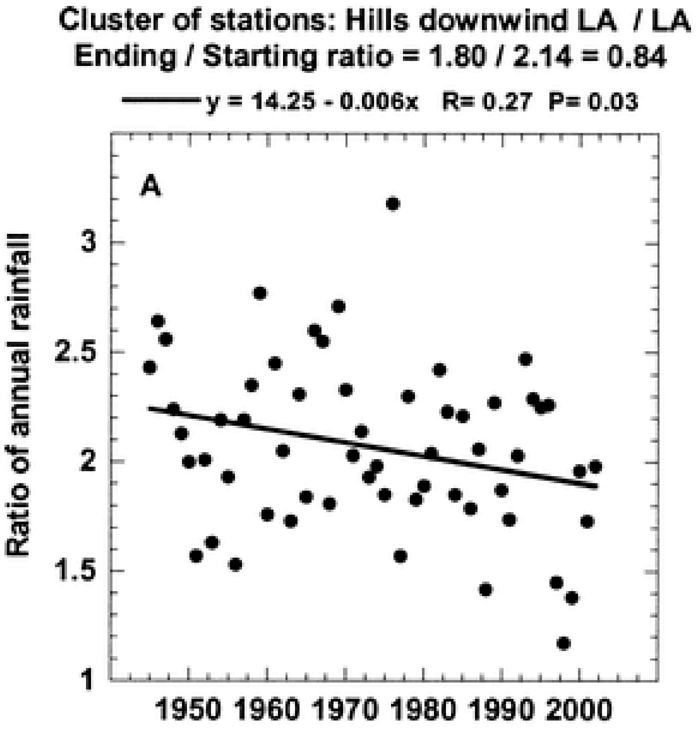
(Lynn et al 2007)



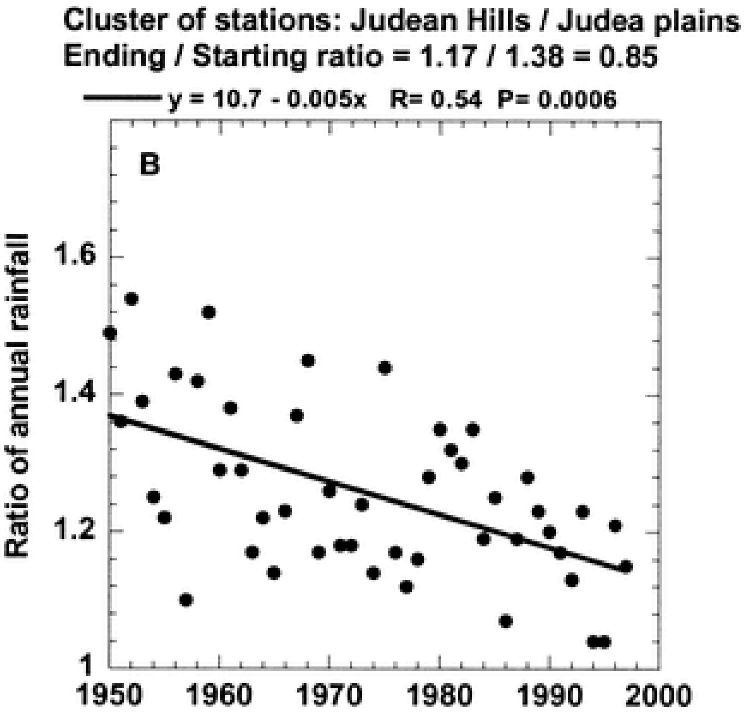
Net decrease in precipitation by 30%

OBSERVATIONS

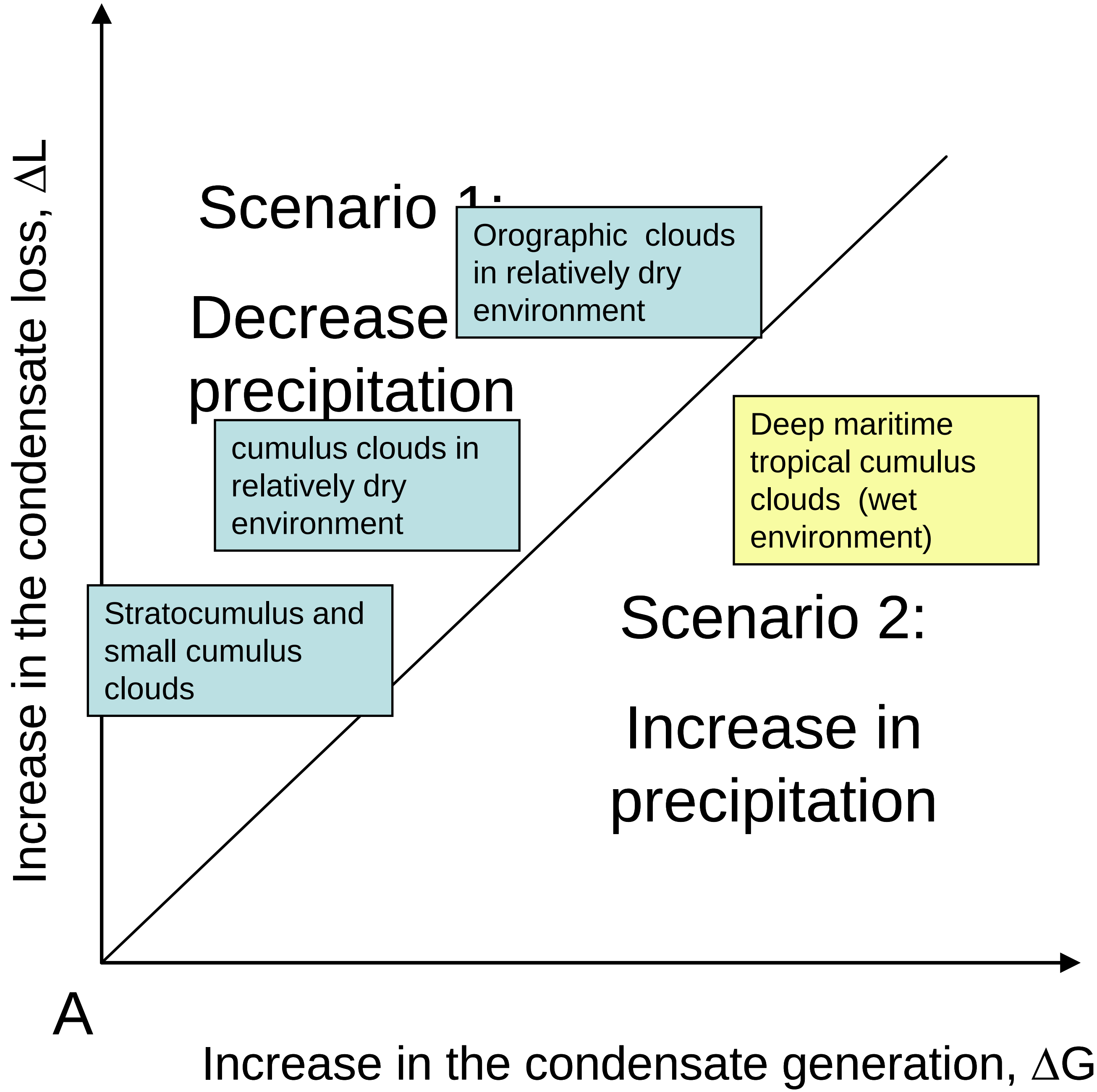
Rainfall trends in California (Left) and Israel (Right) down wind of urban pollution (*Givati and Rosenfeld, 2004*):

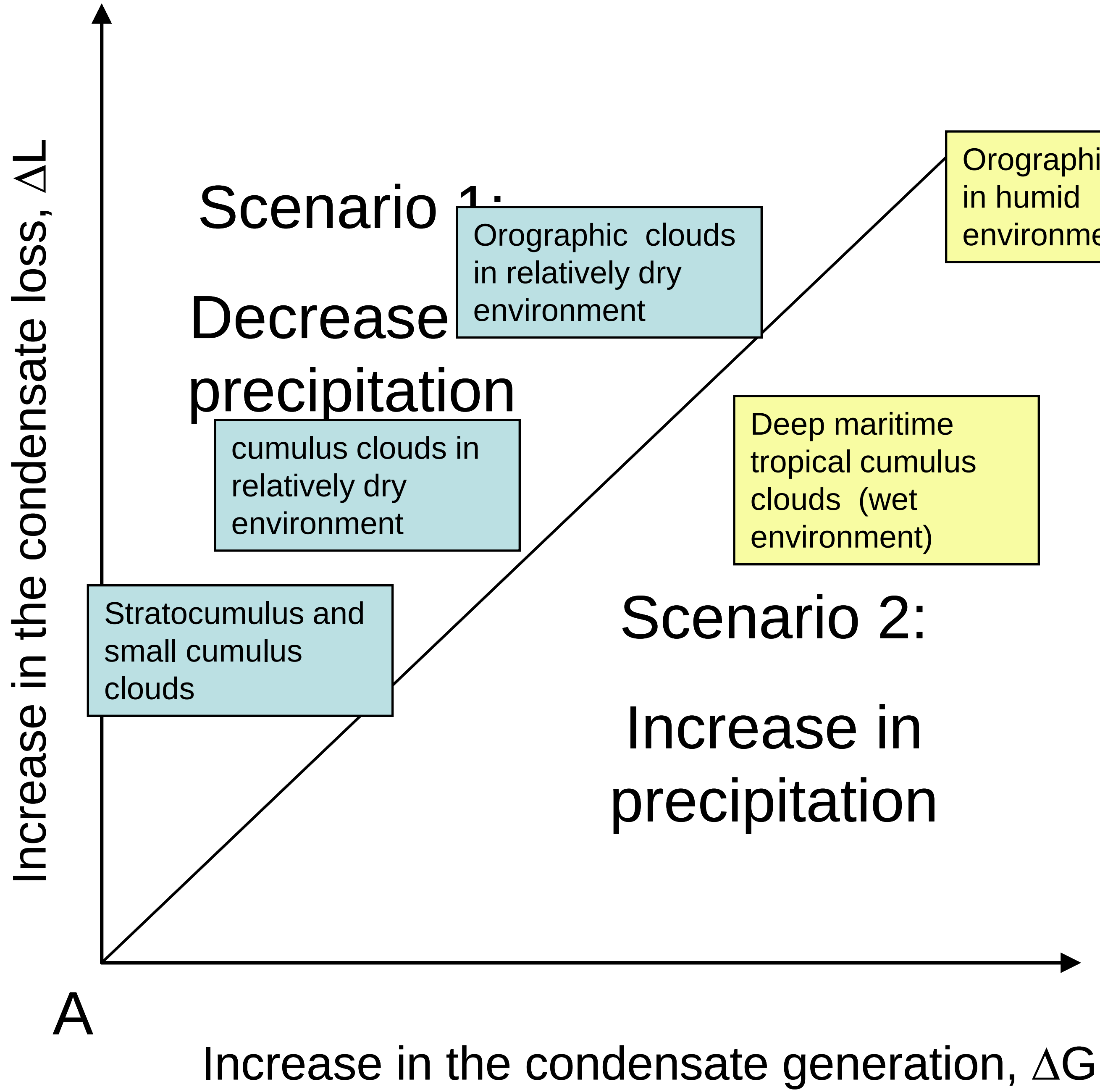


years



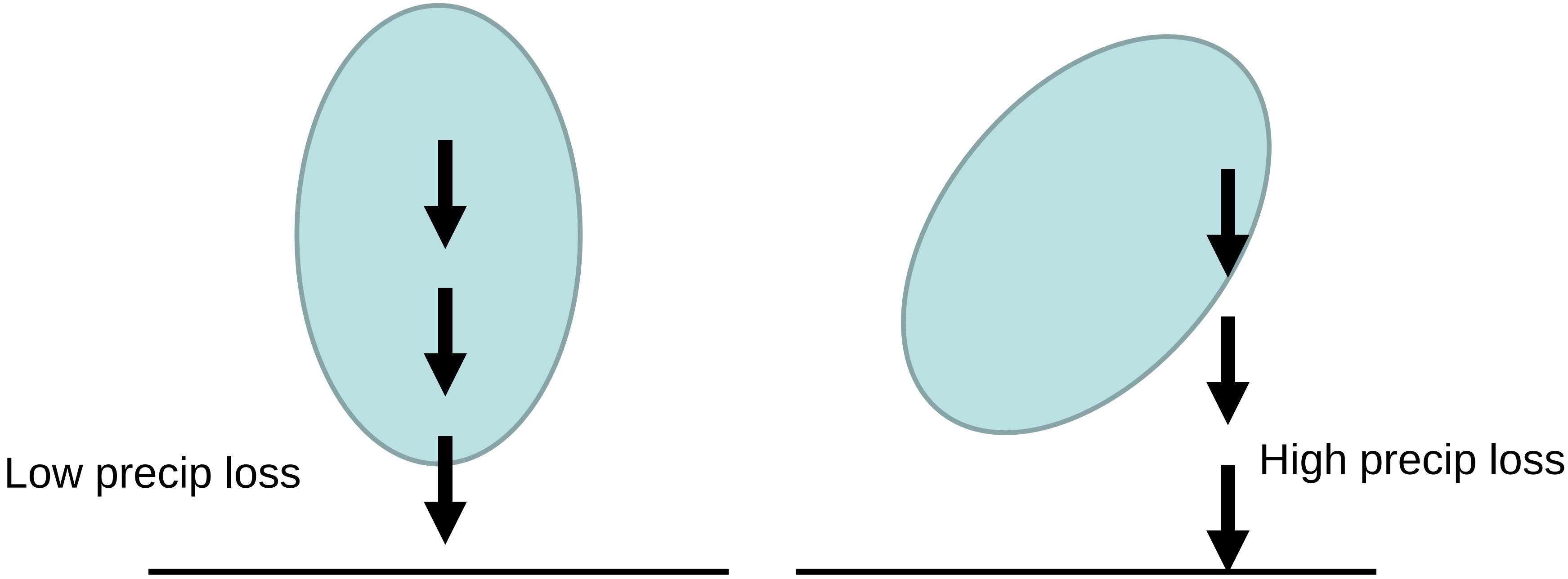
years


Increase in the condensate loss, ΔL
Scenario 1:
Decrease precipitation
Orographic clouds in relatively dry environment
cumulus clouds in relatively dry environment
Stratocumulus and small cumulus clouds
Deep maritime tropical cumulus clouds (wet environment)
Scenario 2:
Increase in precipitation
A
Increase in the condensate generation, ΔG



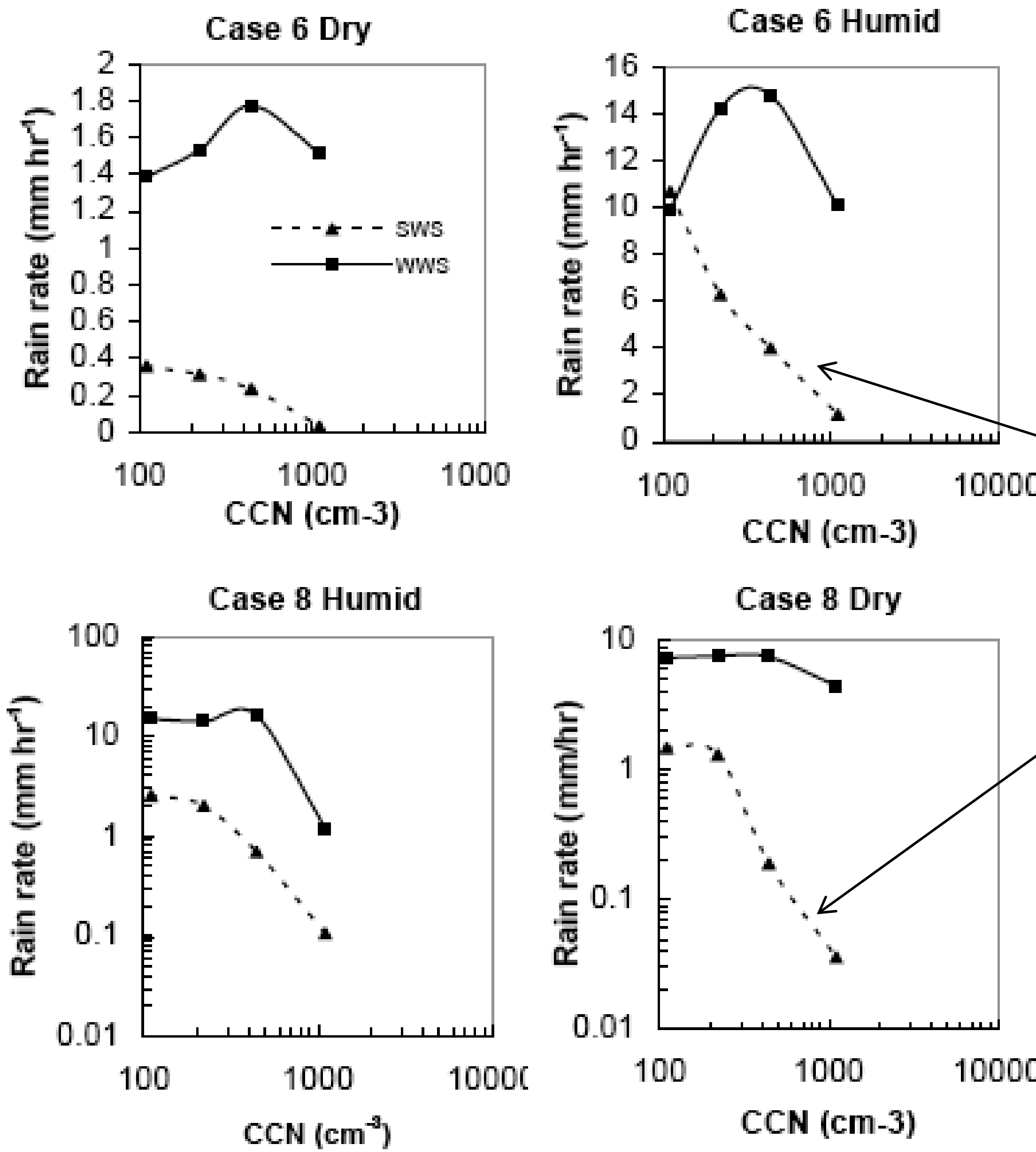
Increase in the condensate loss, ΔL
Scenario 1:
Decrease precipitation
Orographic clouds in relatively dry environment
cumulus clouds in relatively dry environment
Stratocumulus and small cumulus clouds
Orographic clouds in humid environment
Deep maritime tropical cumulus clouds (wet environment)
Scenario 2:
Increase in precipitation
A
Increase in the condensate generation, ΔG

AEROSOL EFFECTS IN SINGLE CLOUDS UNDER DIFFERENT WIND SHEARS

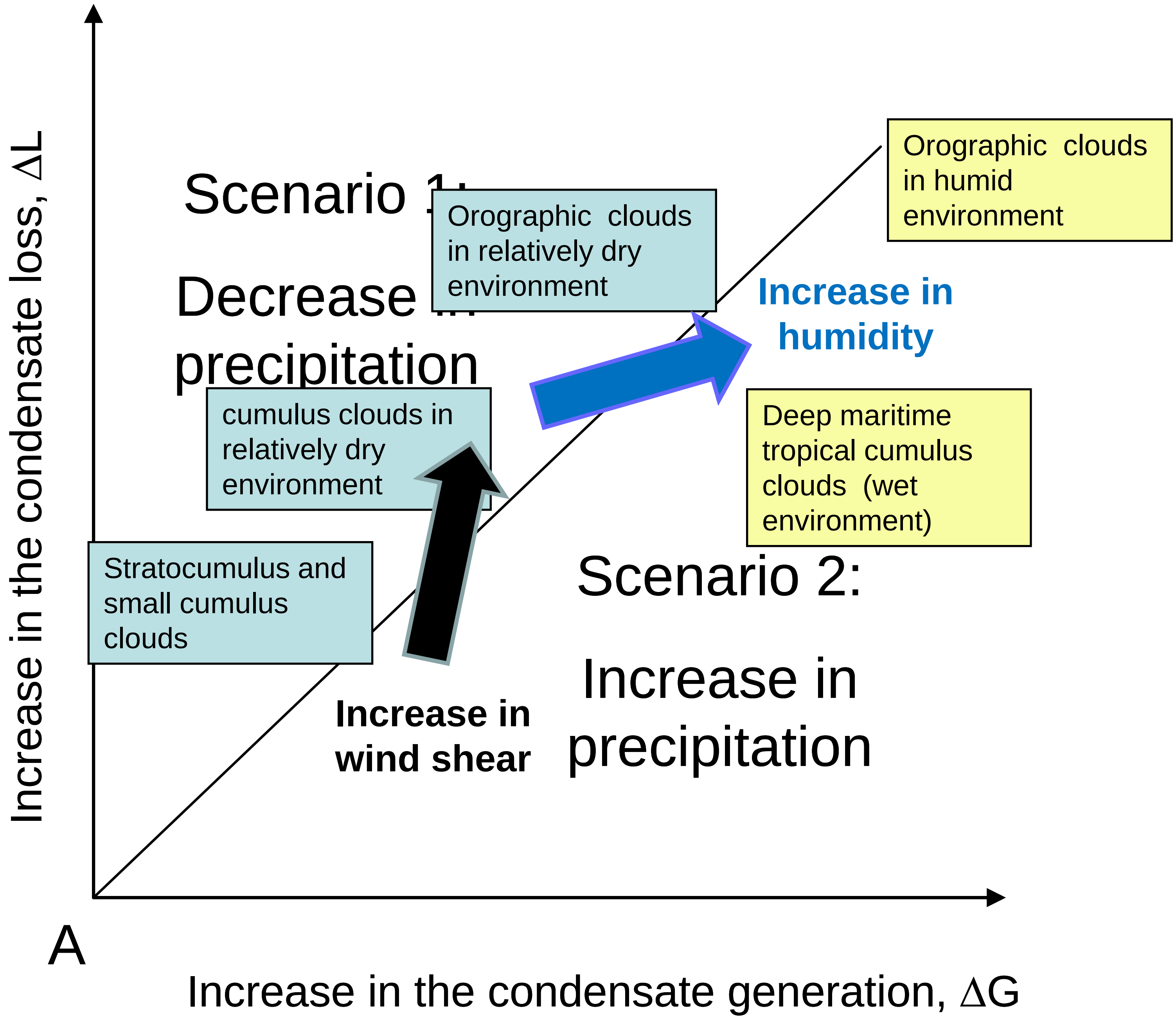


Increase in AP concentration in clouds with strong wind shear increases precipitation loss-→ decrease in precipitation

Jiwen Fan et al 2009



Dramatic decrease in precipitation with increase in aerosol concentration in cases of strong wind shear



Increase in the condensate loss, ΔL
Scenario 1:
Decrease in precipitation
Orographic clouds in relatively dry environment
Orographic clouds in humid environment
Increase in humidity
cumulus clouds in relatively dry environment
Deep maritime tropical cumulus clouds (wet environment)
Stratocumulus and small cumulus clouds
Scenario 2:
Increase in precipitation
Increase in wind shear
A
Increase in the condensate generation, ΔG

CLOUD SYSTEMS

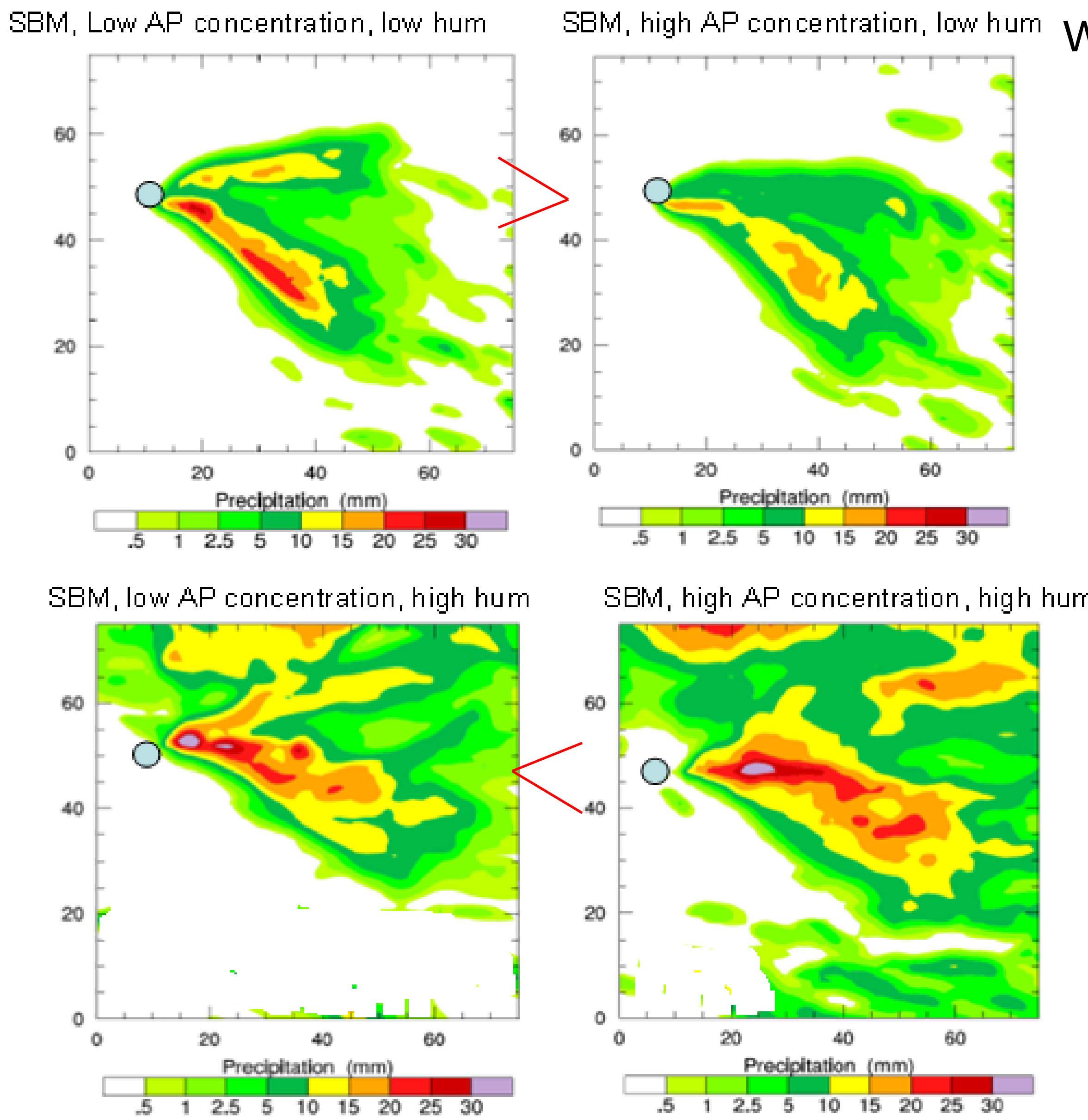
SUPER CELL STORMS (Effects aerosols and humidity)

Khain, and Lynn (2009), WRF with SBM

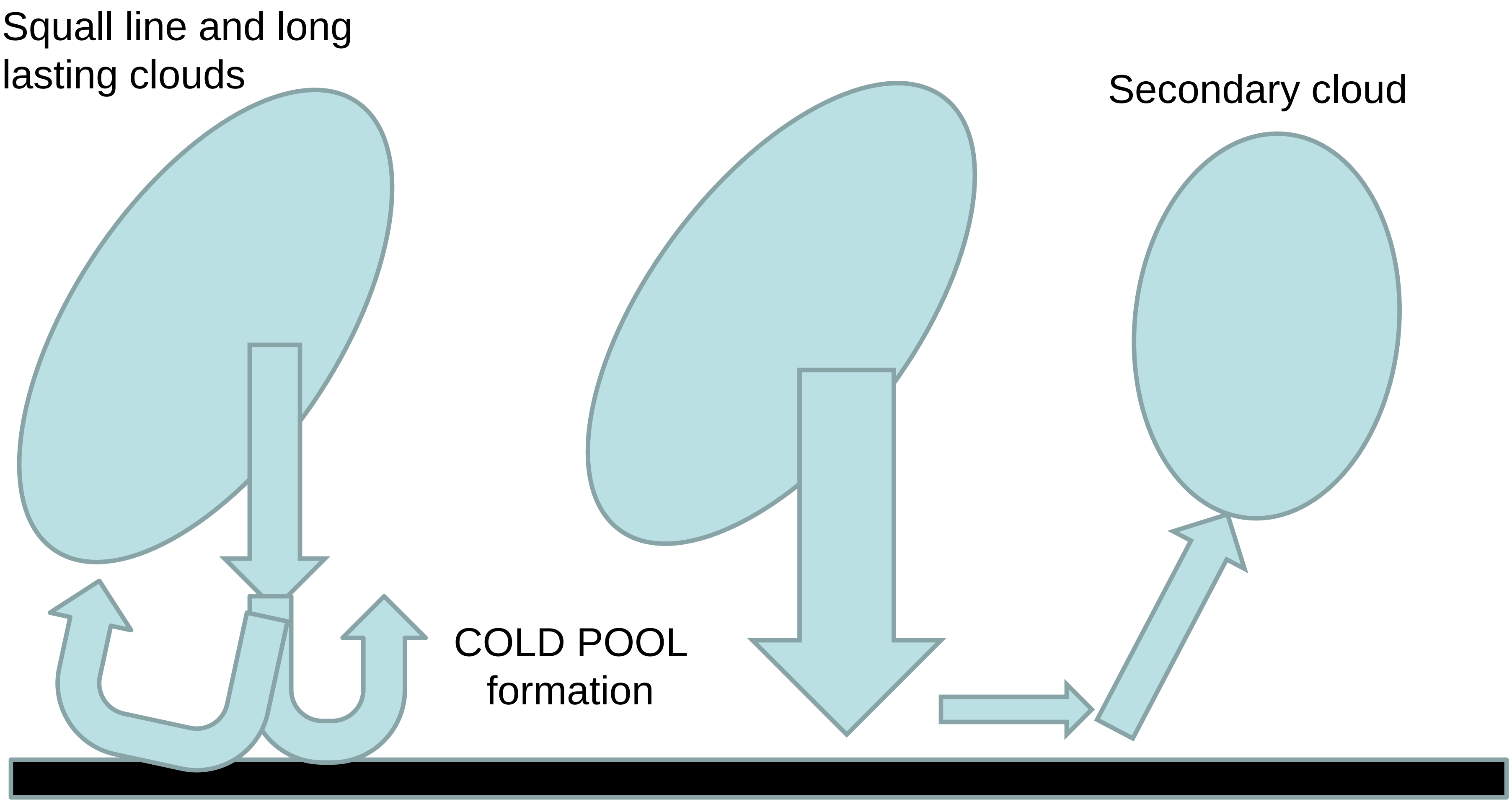
LOW CCN CONC | **HIGH CCN CONC**

MODERATE Humidity

High Humidity



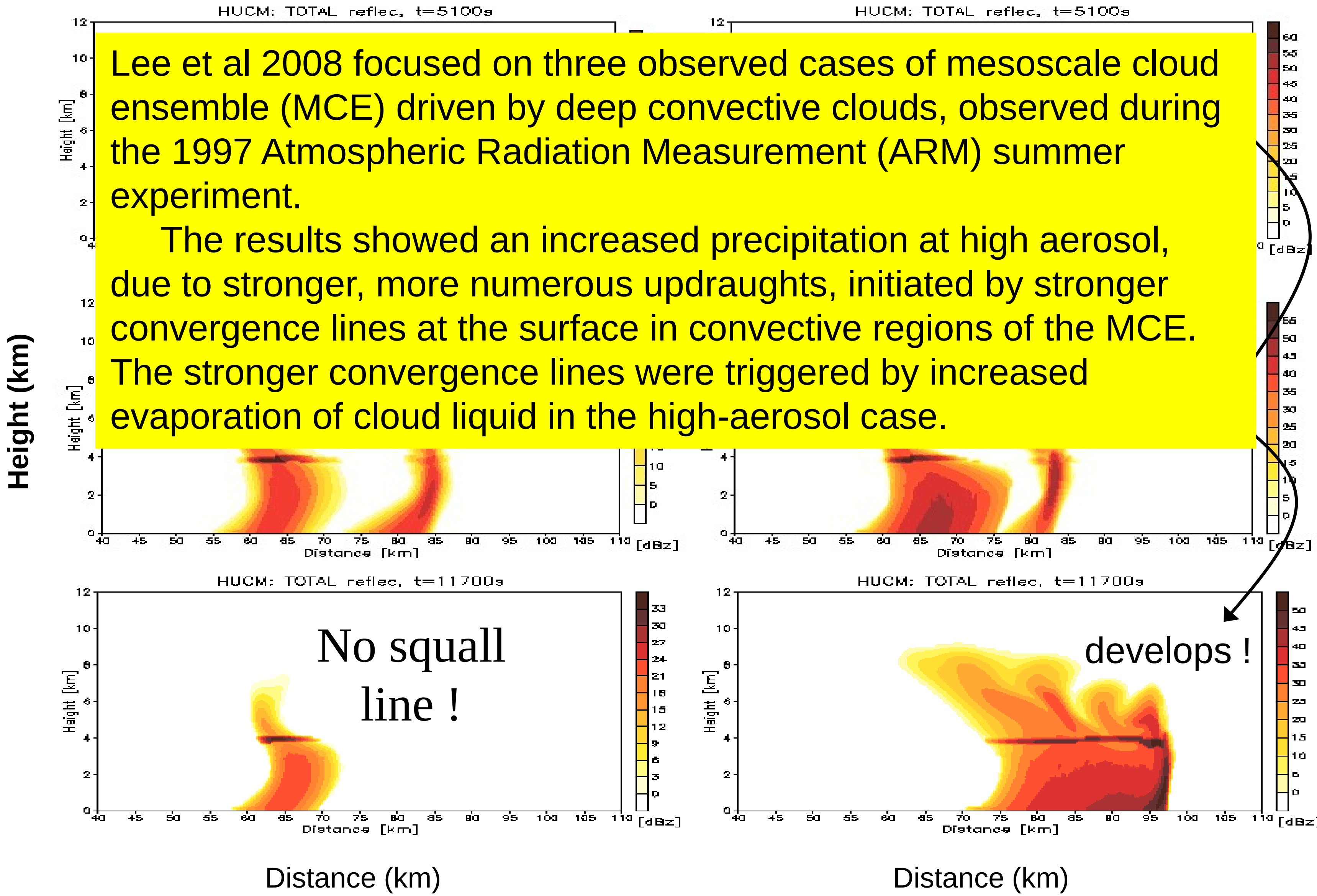
ROLE OF WIND SHEAR IN SQUALL LINES AND CLOUD SYSTEMS
(Khain et al 2005; Tao et al 2007; Lee et al 2008)



Aerosol induced stronger evaporation →stronger downdrafts→ formation of secondary clouds→ dynamically increased precipitation, spatial organization of convection (Khain et al, Tao et al, Lee et al).

A SQUALL LINE: Time evolution of radar reflectivity (*Khain et al, 2003, 2005*)

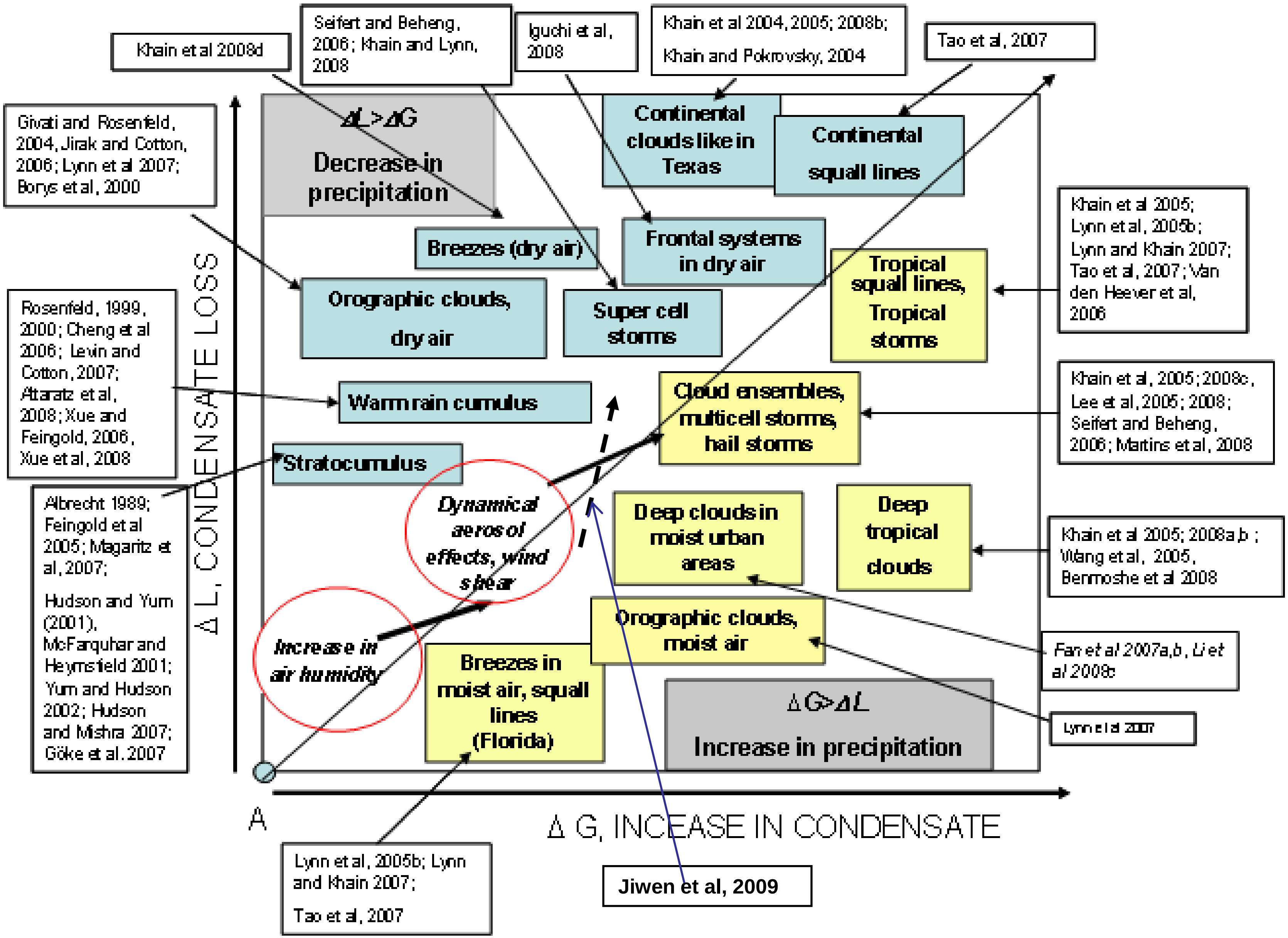
Clean air (Maritime) | Smoky air (Continental)



Lee et al 2008 focused on three observed cases of mesoscale cloud ensemble (MCE) driven by deep convective clouds, observed during the 1997 Atmospheric Radiation Measurement (ARM) summer experiment.

The results showed an increased precipitation at high aerosol, due to stronger, more numerous updraughts, initiated by stronger convergence lines at the surface in convective regions of the MCE. The stronger convergence lines were triggered by increased evaporation of cloud liquid in the high-aerosol case.

EFFECTS OH HUMIDITY AND WIND SHEAR allows classification of precipitation response to aerosols in single clouds and cloud ensembles



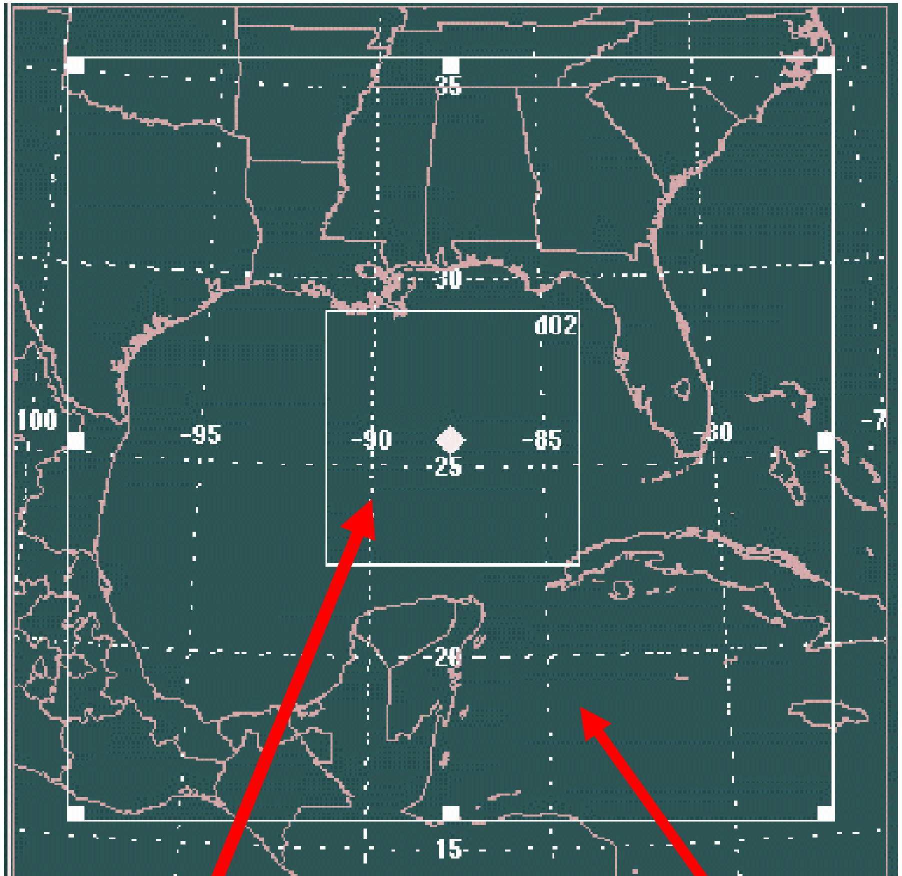
EFECT OF AEROSOLS ON MESOSCALE SYSTEMS (TROPICAL CYCLONES)

FACTORS:

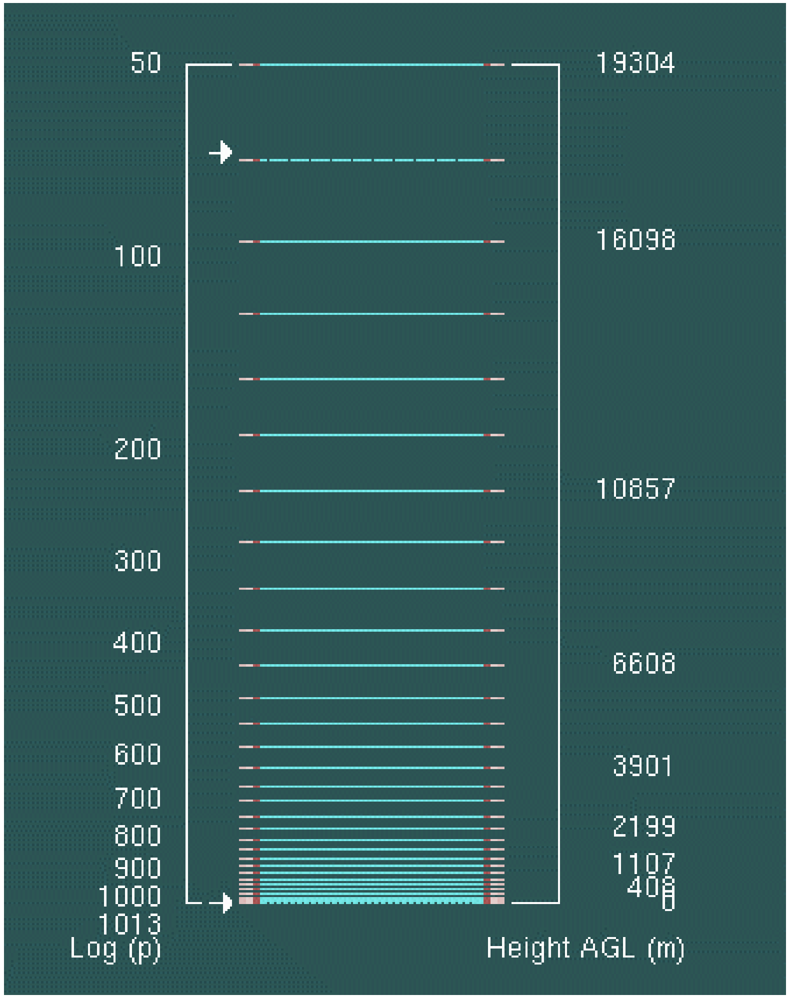
All previous +SPATIAL REDISTRIBUTION OF LATENT HEAT RELEASE

GRID STRUCTURE OF WRF_SBM USED FOR SIMULATION OF HURRICANE KATRINA

resolution of the finest grid 3 km

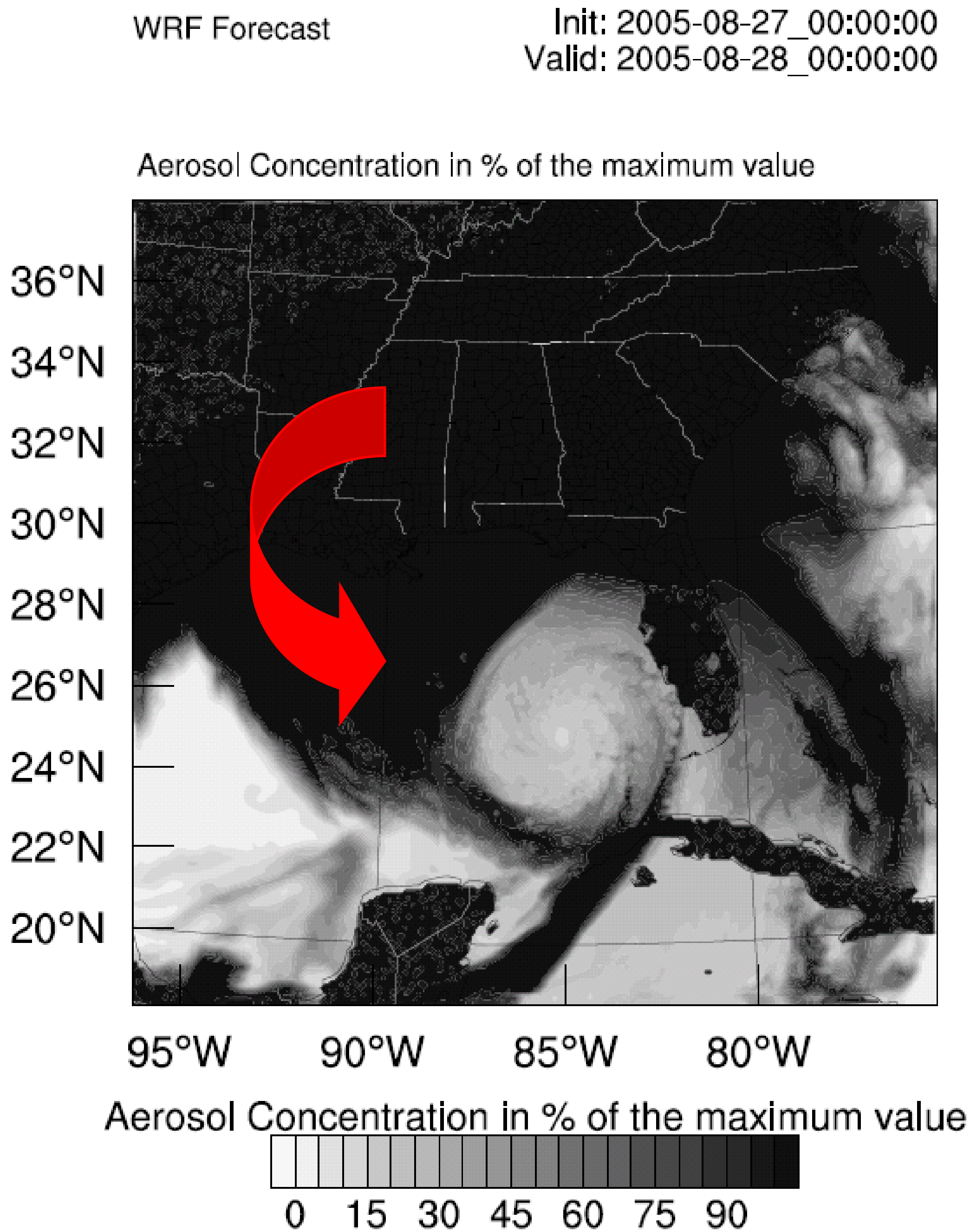


31 levels, terrain-following vertical coordinates



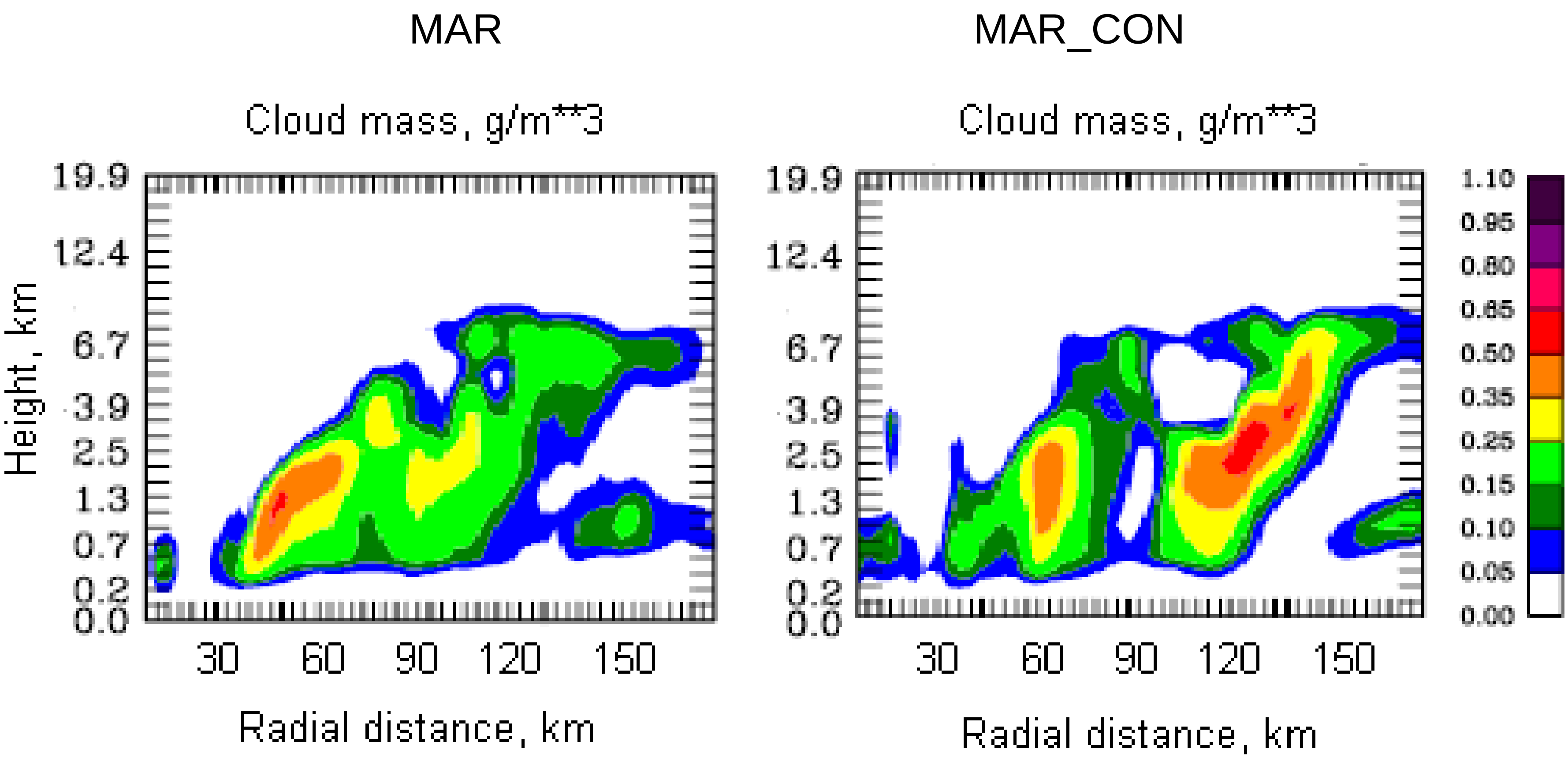
Spectral bin microphysics is used on movable fine grid

Bulk parameterization



Khain et al 2008, 2010

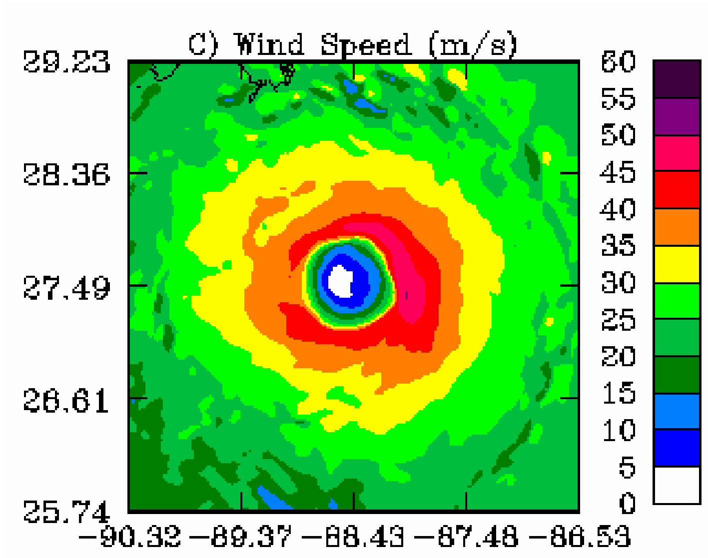
The vertical cross-section of azimuthally averaged CWC

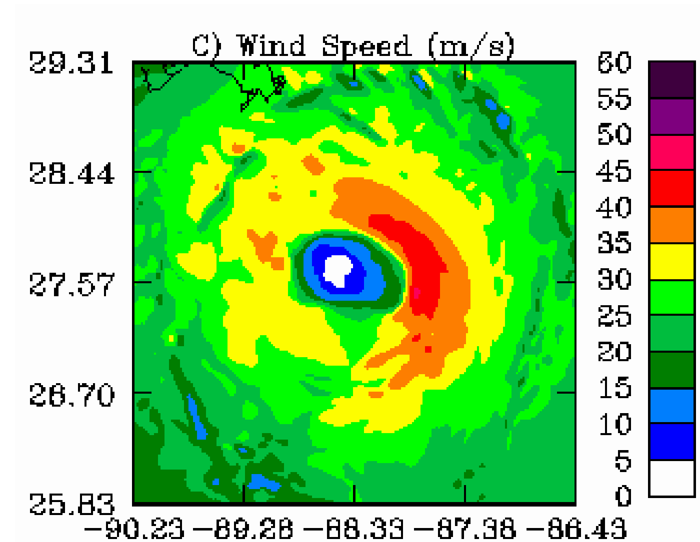


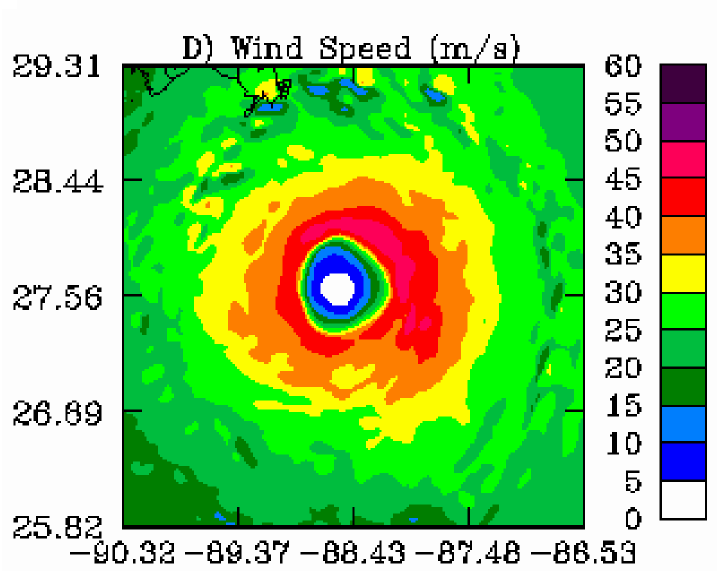
Khain et al 2010

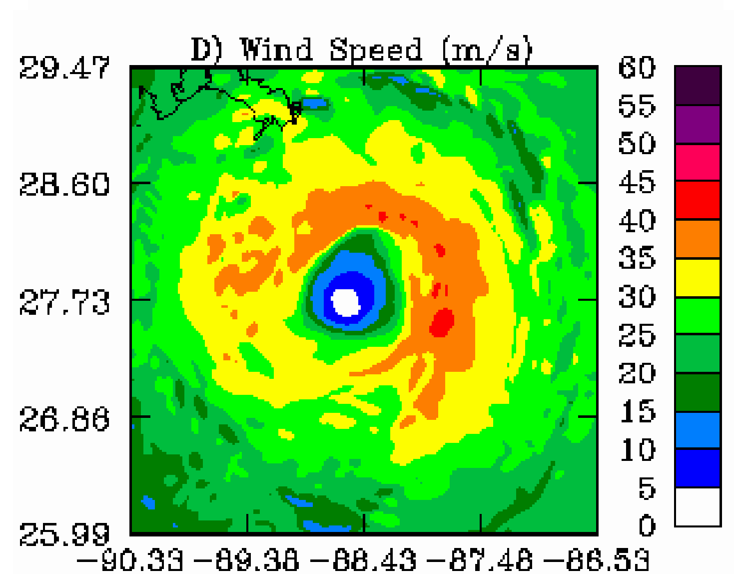
Maximum wind speed

Low CCN concentration	Effects of continental aerosols are taken into account









TC GENESIS

TD Debby 2006

Trajectory of TS Debby and the grid configuration used in the WRF-SBM model

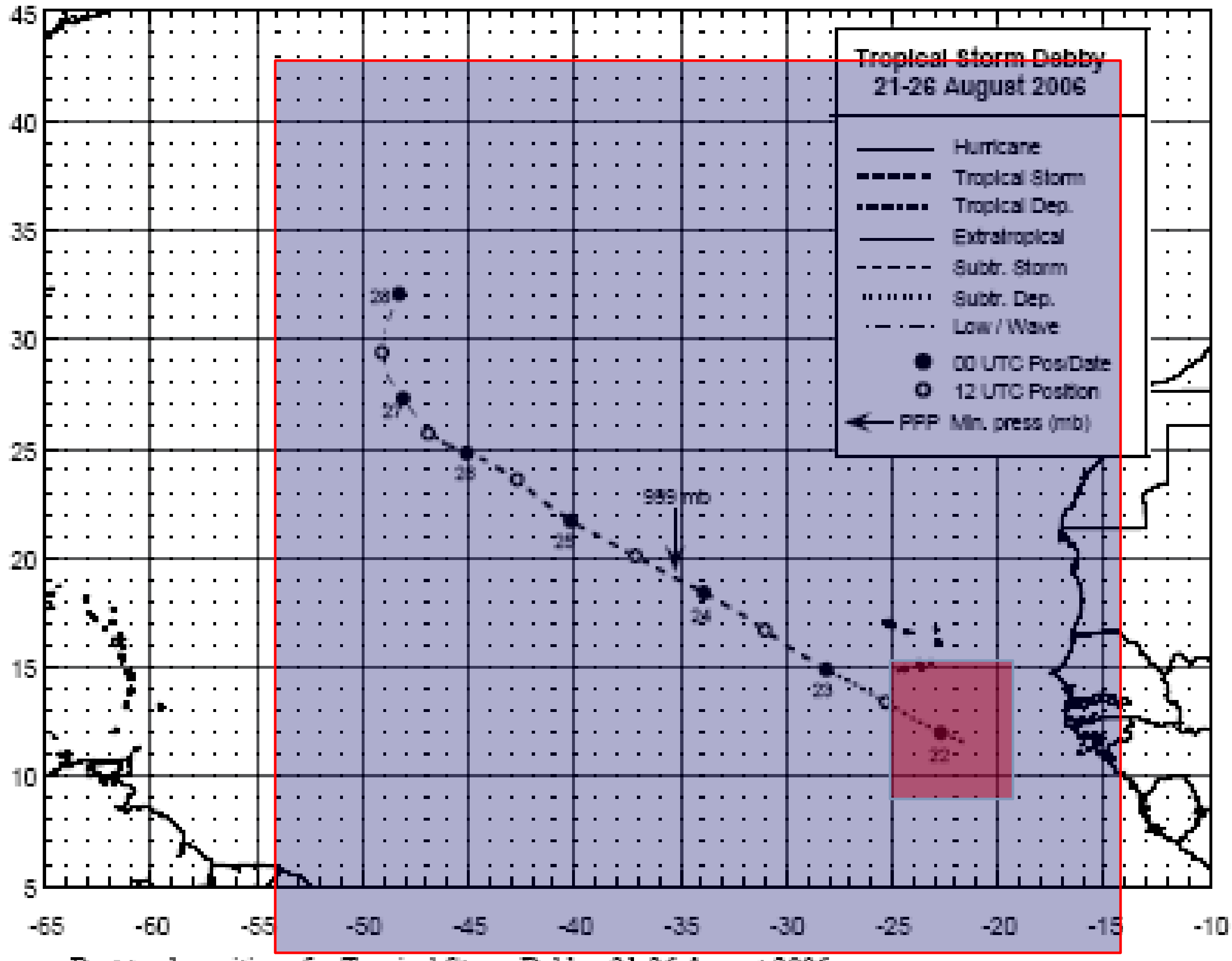
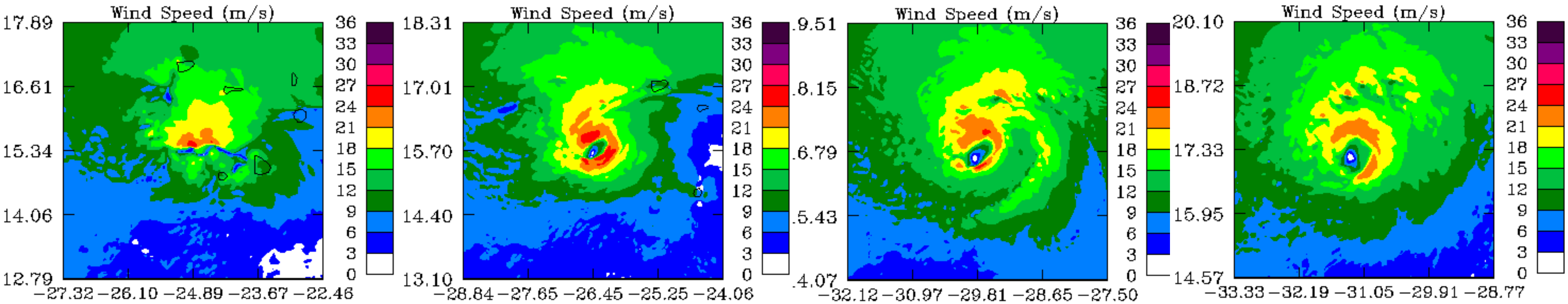


Figure 1. Best track positions for Tropical Storm Debby, 21-26 August 2006.

Khain et al 2010

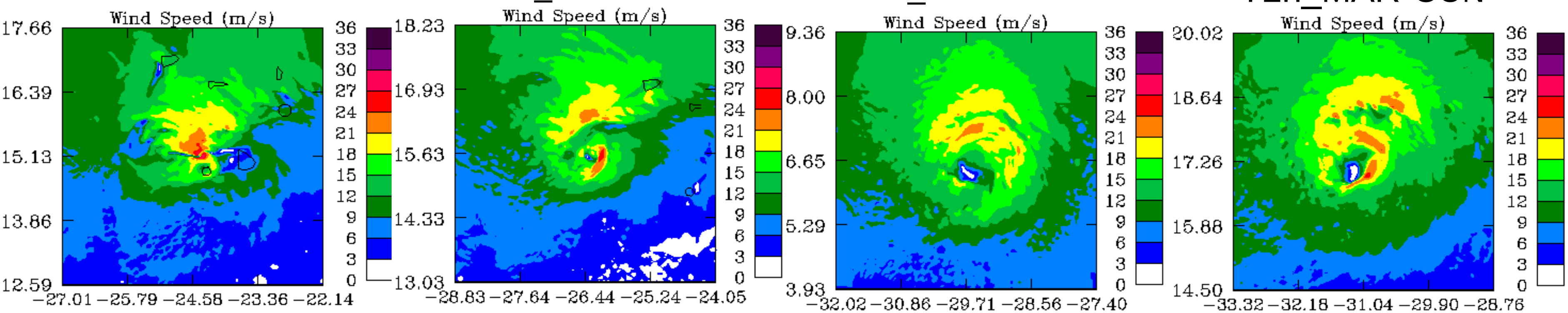
LOW AEROSOL CONCENTRATIONS

45h_MAR | 54h_MAR | 66h_MAR | 72h_MAR



INTRUSION OF SAHARAN DUST INTO TD

45h_MAR-CON | 54h_MAR-CON | 66h_MAR-CON | 72h_MAR-CON



Aerosols hinder TD development via increase in convection (and precipitation) at TC periphery.

CONCLUSIONS

1. THE EXISTENCE OF THE AEROSOL EFFECTS ON MICROPHYSICS , DYNAMICS AND PRECIPITATION IS OBVIOUS FROM BOTH OBSERVATIONS AND NUMERICAL SIMULATIONS

2. EFFECTS OF AEROSOLS DEPEND ON ENVIRONMENT CONDITIONS: humidity, wind shear, stability of the atmosphere, etc.

3. IN GENERAL AEROSOLS TEND INTENSIFY DEEP CONVECTION AND TO SUPPESS PRECIPITATION FROM SMALL CLOUDS

4. IT IS POSSIBLE TO PROPOSE QUALITITATIVE CLASSIFICATION OF AEROSOL EFFECTS ON PRECIPITATION OF SINGLE CLOUDS AND CLOUD ENSEMBLES (LIKE STORMS AND SQUALL LINES).

QUANTITATIVELY EFFECTS OF AEROSOLS CAN BE DERIVED BY USING STATISTICS OF DIFFERENT METEOROLOGICAL SITUATIONS

5. AEROSOLS AFFECT SPATIAL DISTRIBUTION OF CONVECTION IN MESOSCAL SYSTEMS affecting their intensity and precipitation

It is the most difficult to evaluate the potential effect of aerosols on precipitation, when increase in precipitation at TC periphery weakens TC or TD

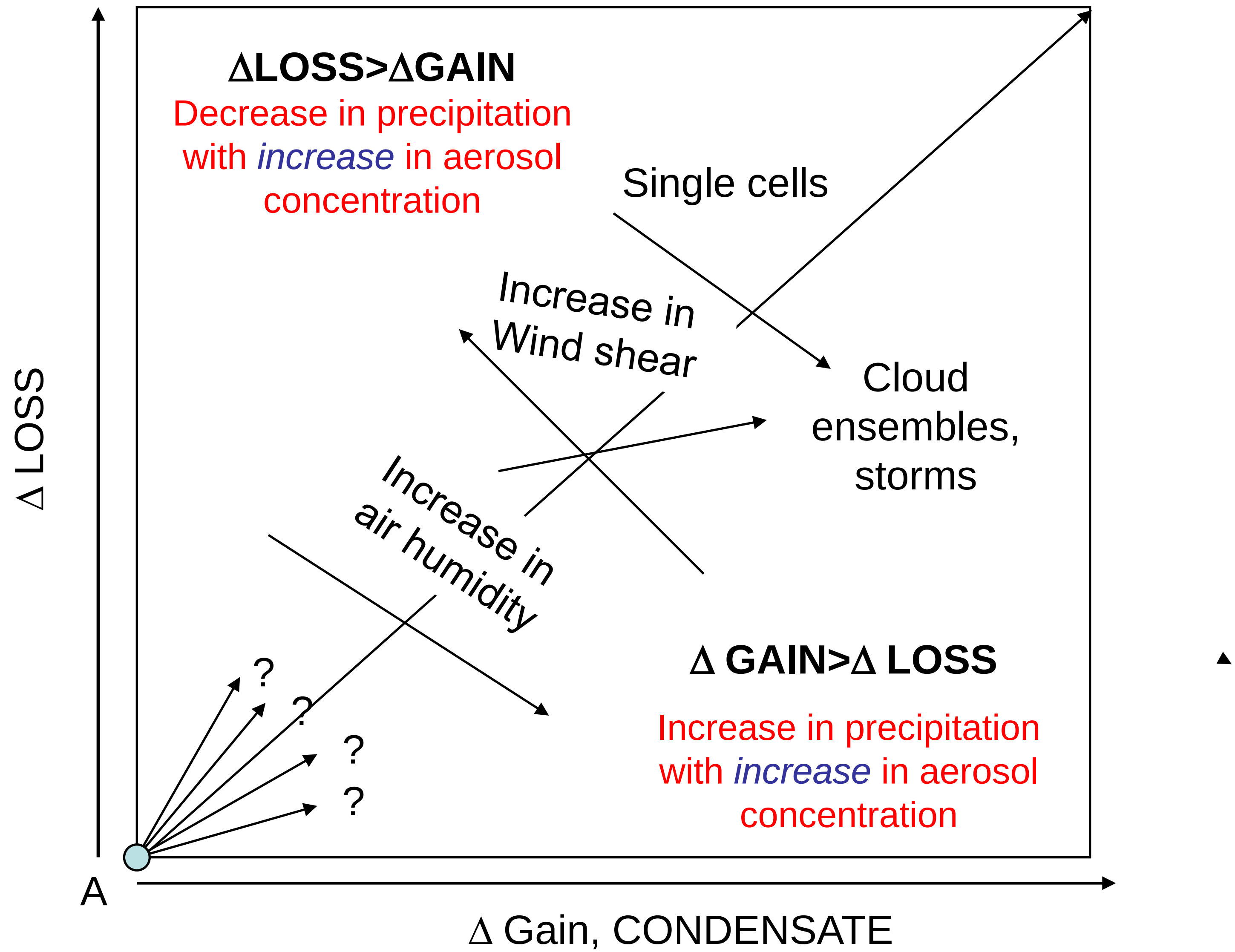
The problems which were not discussed

6. Effects of aerosols on clouds and cloud systems developing in case of low freezing area takes special consideration

7…..
8…..

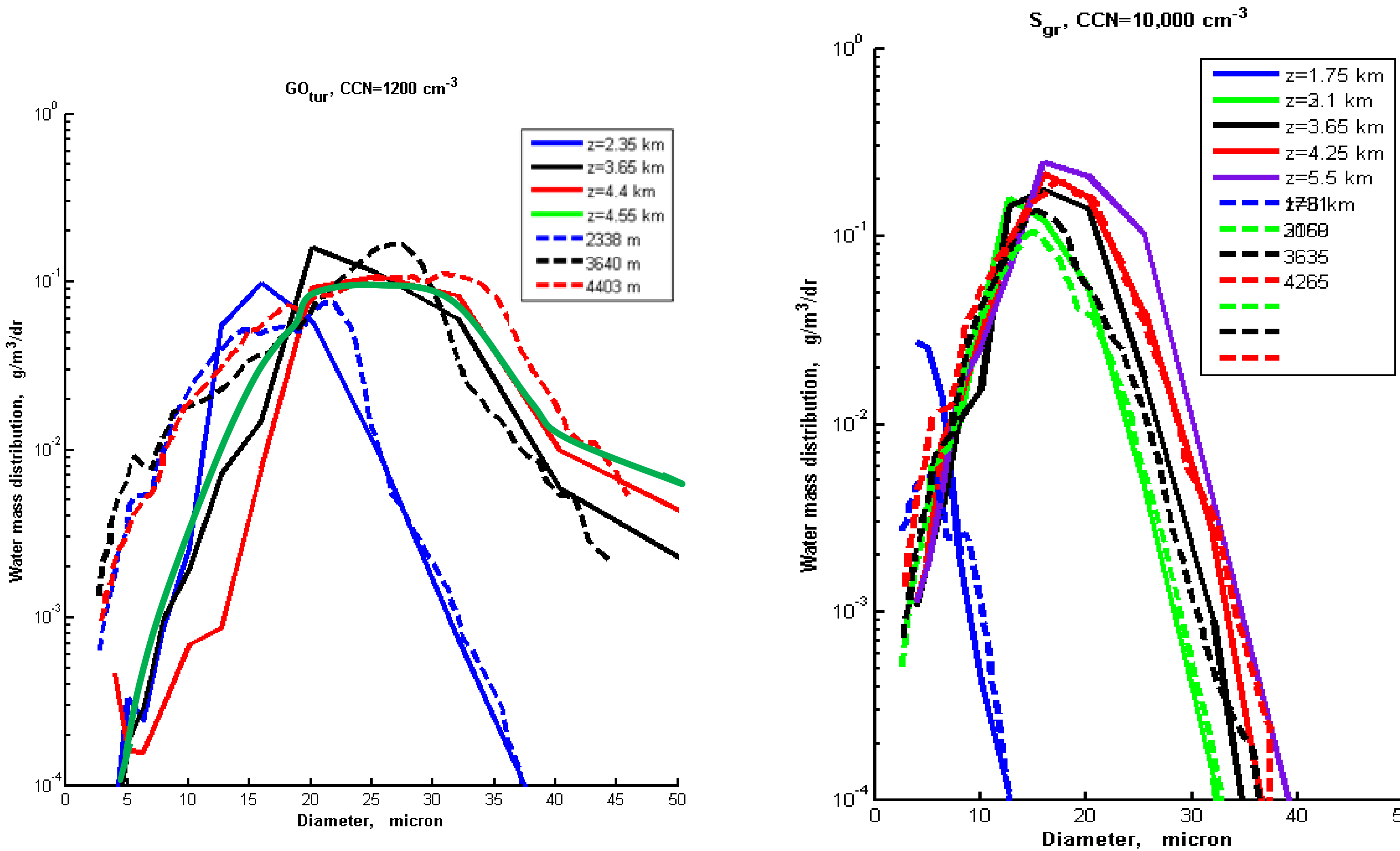
THANK YOU!

Possible scenarios of aerosol effects on precipitation



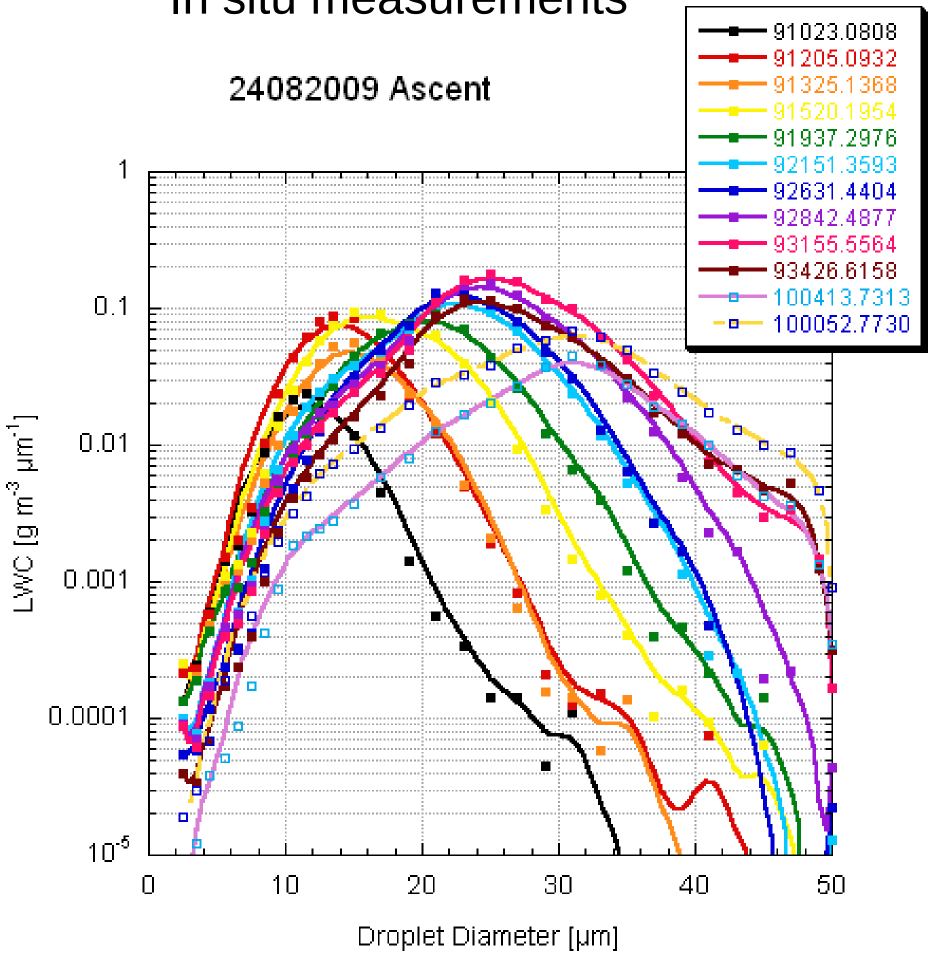
4. AEROSOLS AFFECT SPATIAL DISTRIBUTION OF CONVECTION IN MESOSCAL SYSTEMS affecting their intensity and precipitation

This is the most difficult to evaluate the potential effect of aerosols on precipitation, when increase in precipitation at TC periphery weakens TC or TD

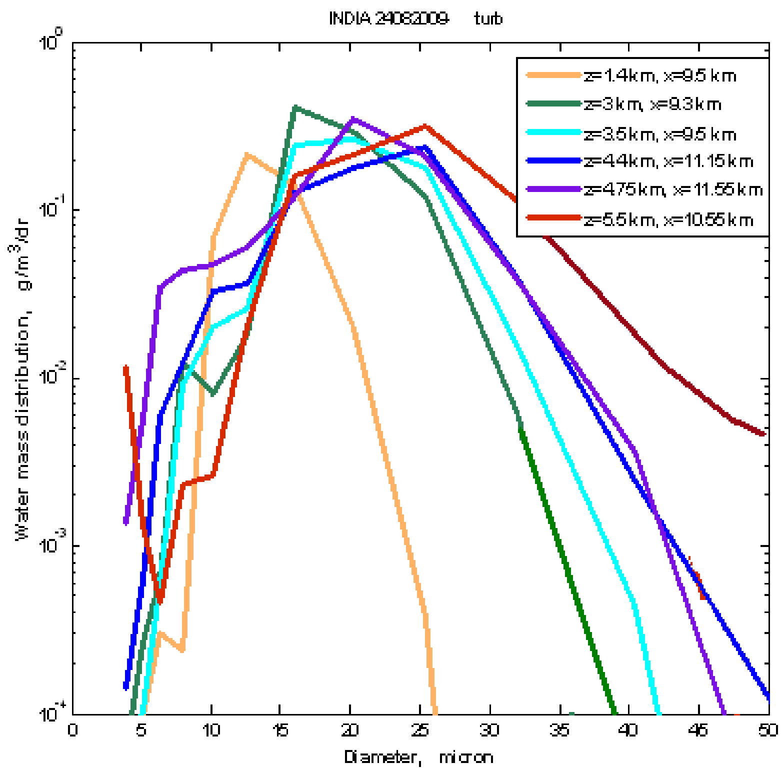


Mass distribution functions at different heights calculated in the GO_ (left) and Smoky_tur (right) simulations (solid lines). The distributions measured in situ at 5 Oct 2002 in the green –ocean clouds at nearly the same height levels are plotted by dashed lines (after Andreae et al 2004 and Freud et al 2004).

In situ measurements



Numerical simulations

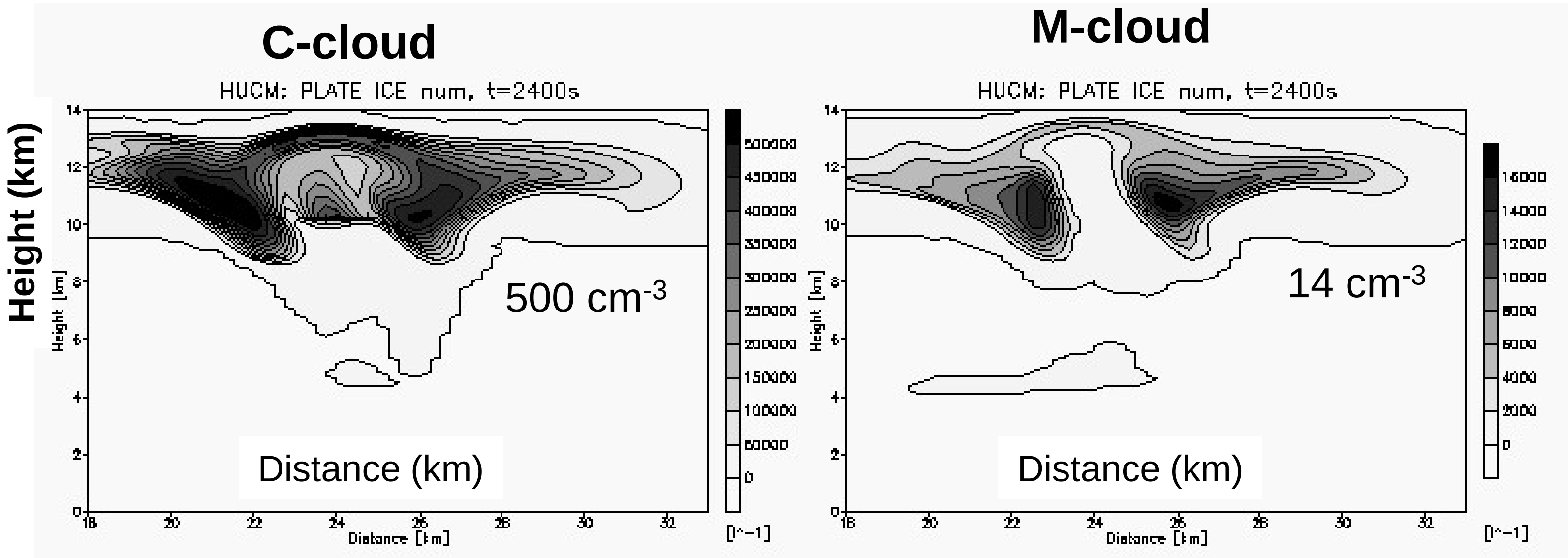


Example 3:

Continental clouds in very dry air

ΔLoss>ΔGain

2D HUCM: Concentration of ice crystals in Texas summertime clouds (very dry air, isolated clouds) (*Khain et al 2001; Khain and Pokrovsky, 2004)*



Results:

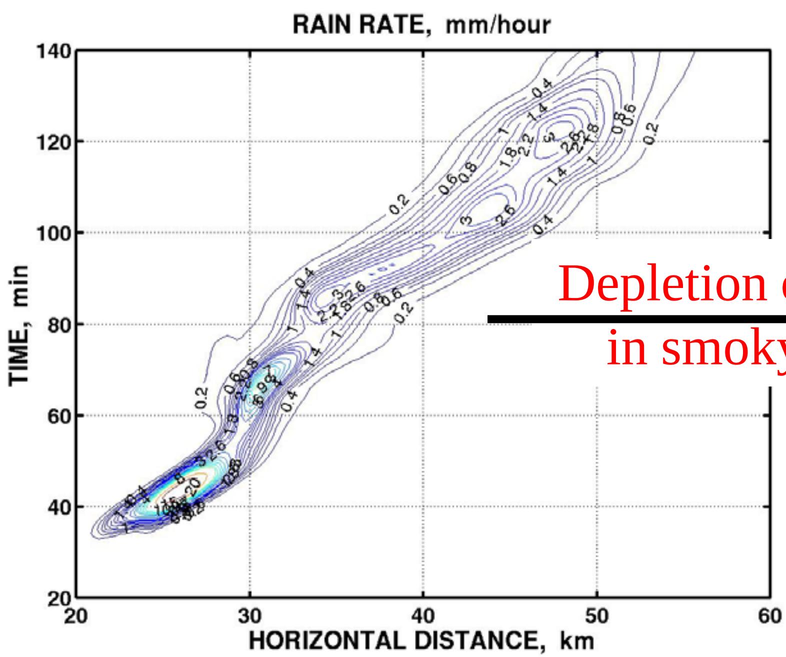
1) Aerosols increase ice contents at the upper levels and increases the area of cloud anvils (ice anvils)

2) Formation of a large amount of crystals at high levels represents loss in precipitating mass

TEXAS: CONTINENTAL (UNSTABLE) CONDITIONS

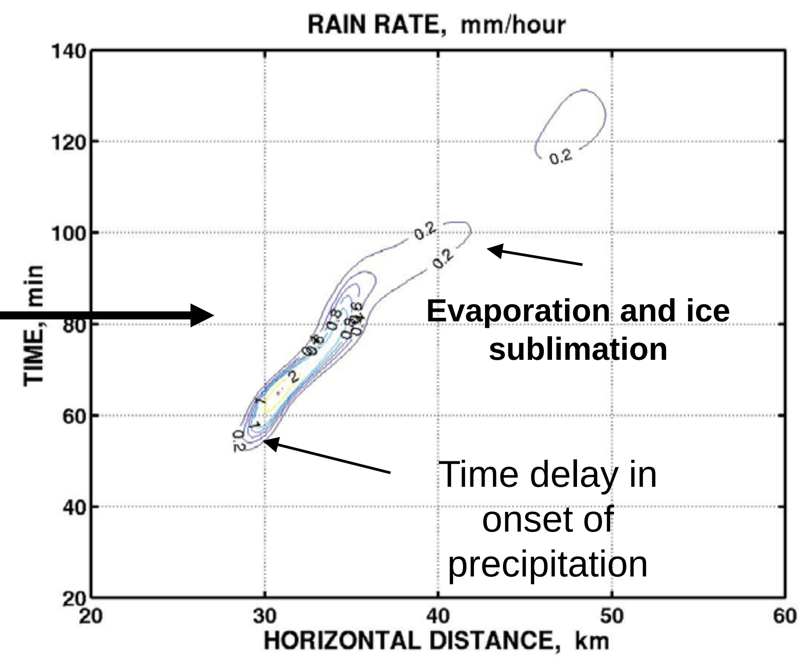
Khain and Pokrovsky (2004-JAS)

maritime aerosol



Depletion of rain
in smoky air

continental aerosol



Result:

Aerosol decrease (even deplete) precipitation because of larger loss of precipitation by sublimation and evaporation within a dry air environment

The role of atmospheric humidity and wind shear

Aerosols (not including GCCN) inhibit precipitation:

Rosenfeld 1999, 2000 (small clouds+droplets are small);

Givati and Rosenfeld 2004 (Dry atmosphere, orographis clouds)

Tao et al (1995), Ferrier et al (1996

Khain et al, 2001 (very dry atmosphere, high instability);

Khain and Pokrovsky (2004) (very dry atmosphere, high instability);

Khain et al (2004a,b)(dry atmosphere)

Axel et al (2004) (dry atmosphere, single clouds);

Tao et al (2004)(dry atmosphere)

Teller and Levin(2005) (cold cloud base, single cloud)

Lynn et al (2006)(orographic clouds, dry atmosphere)

Borys et al (2000)(orographic clouds, dry atmosphere)

Jirak and Cotton (2006)(orographic clouds, dry atmosphere)

Khain et al (2007) dry atmosphere (Brazil)

Tao et al (2007) continental squall line

Khain and Lynn (2007) dry air, supercell storm

Aerosols can increase precipitation:

Ohashi and Kida 2002 (breeze, wet conditions)

Shepherd and Burian 2003 (wet conditions)

Amiranashvili et al 2004 (**wet conditions, deep thunderstorms)**

Filho et al (2004) (wet conditions, breeze circulation)

Khain et al (2005-QJRMS) (Wet air, tropical clouds)

Axel et al (2004) (wet air);

Axel and Beheng (2004)

Tao et al (2004) (wet air, squall line)

Van den Heever et al (2004) (cloud system, wet)

Lynn et al (2005a,b- Florida wet air, squall line)

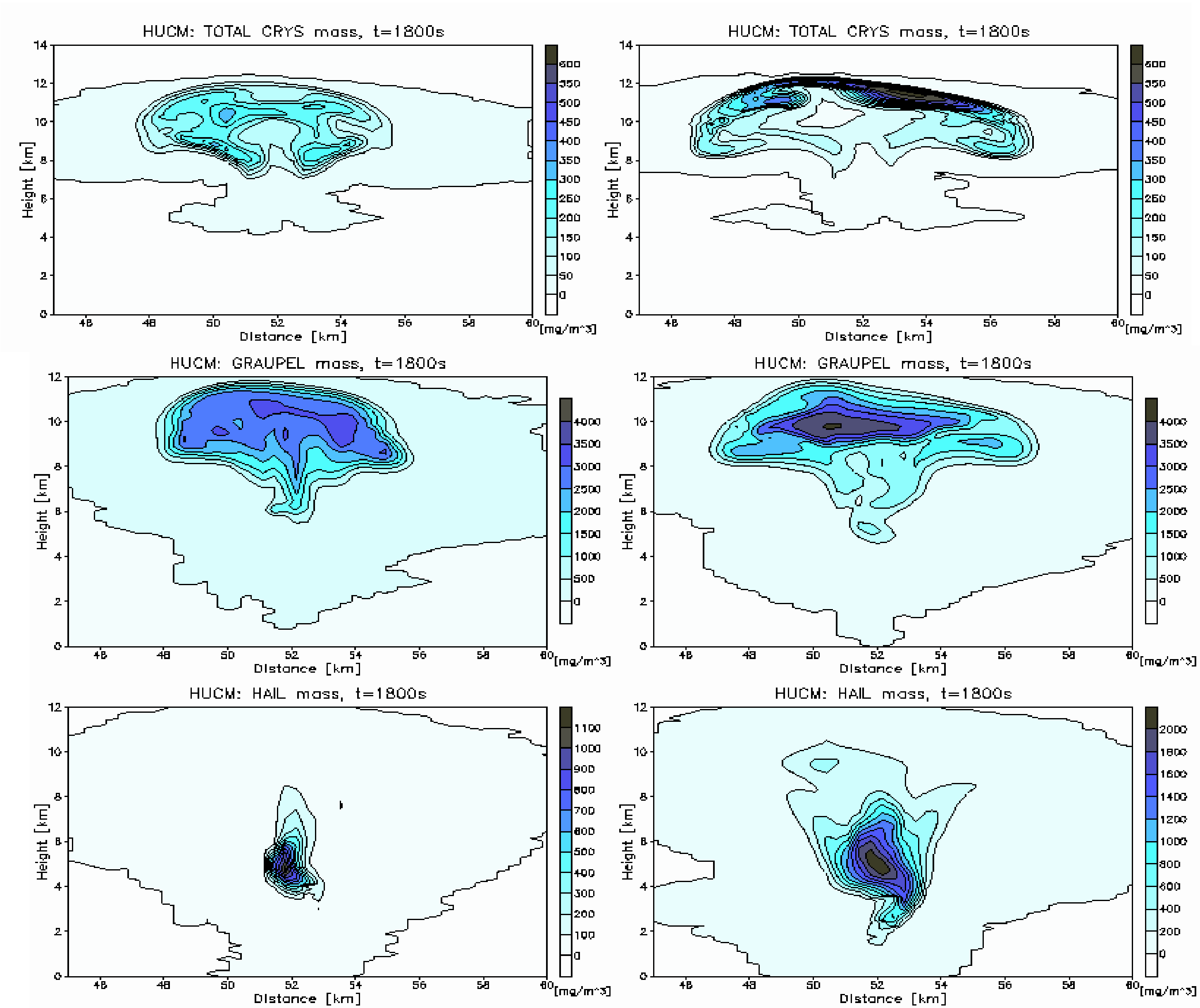
Khain et al (2007-wet, tropical convection)

Tao et al (2007) –TOGA CORE (wet, squall line)

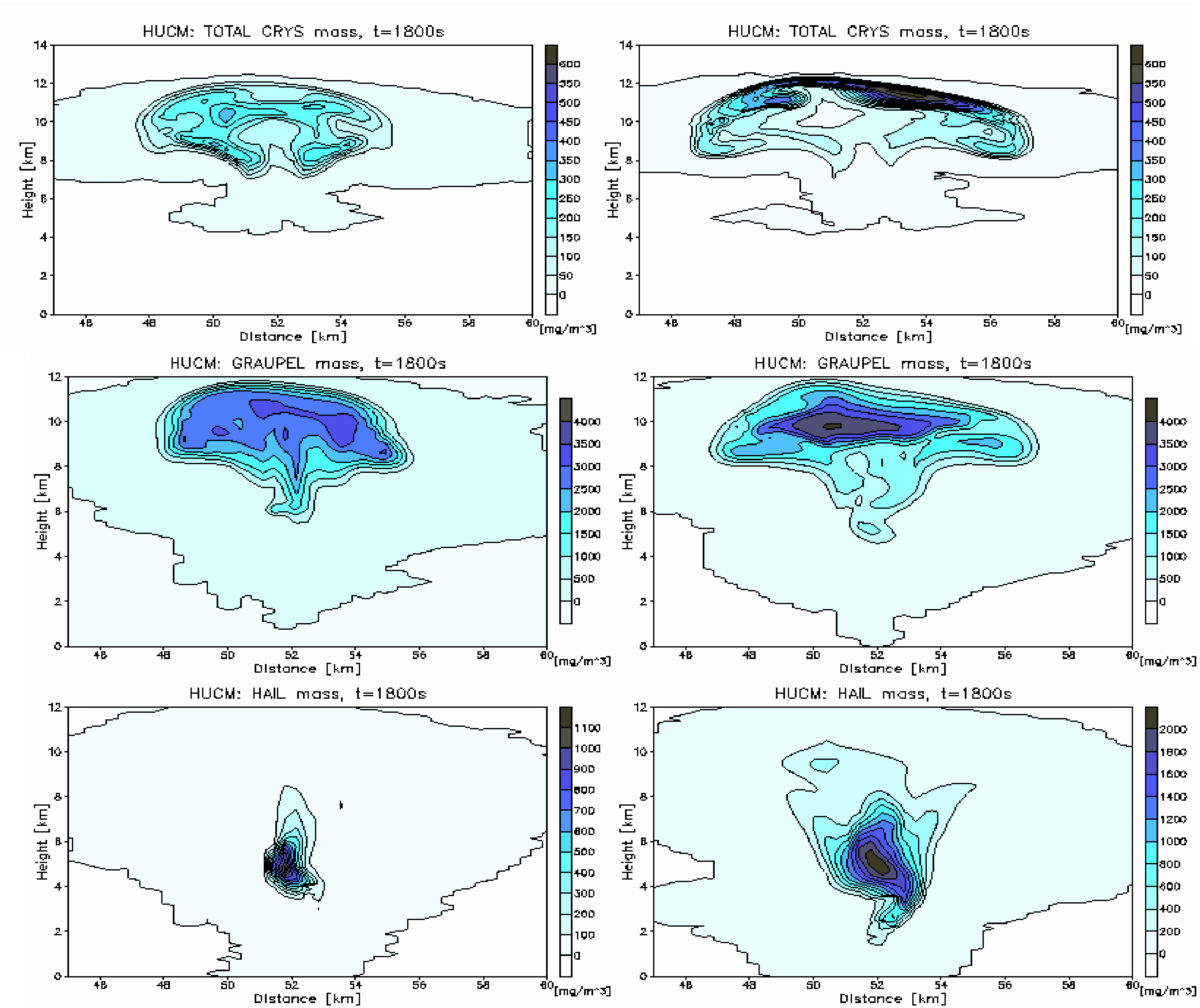
Khain and Lynn (2007) supercell storm, wet air)

Wang (2005) (tropical convection)

LOW CCN concentration HIGH CCN concentration



LOW CCN concentration HIGH CCN concentration



LANDFALL: Maximum wind speed

Low CCN concentration

Effects of continental aerosols are taken into account