

Aerosol Influences on Clouds and Precipitation

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Outline

- Brief overview of RAMS physics.
- Drizzling boundary layer cloud simulations.
- Simulations of pollution effects on winter orographic clouds.
- Simulations of aerosol pollution effects on Arctic stratus clouds
- Simulations of African dust influence on Florida thunderstorms.
- Simulations of urban pollution effects on convective storms.
- Simulations of aerosol influences on tropical cyclones
- Summary and conclusions.

RAMS microphysics with explicit aerosol nucleation

Cloud Droplet Nucleation

Number nucleated obtained from lookup table as a function of

{
 CCN number concentration
 Vertical velocity
 Temperature

Lookup table generated previously (offline) from detailed parcel-bin model

$$N_{c1} = N_{ccn} S_w^b$$

$$N_{c2} = N_{gccn} ; S_w > 0.0$$

Ice Crystal Nucleation

Ice nucleation follows the approach described by Meyers et al. (1992):

$$N_i = N_{IN} \exp [12.96 (S_i - 1)]$$

$T < -5^\circ\text{C}$; $r_v > r_{si}$ (supersaturation with respect to ice), and $T < -2^\circ\text{C}$; $r_v > r_{sl}$ (supersaturation with respect to liquid).

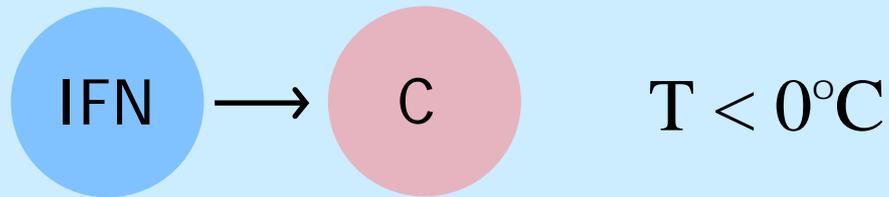
Secondary ice particle production model in RAMS is based on Mossop (1976). In MKS units, the formula is:

$$N_i = 9.1\text{e-}10 \times B \times N_{24} \times (N_{13})^{.93}$$

where B increases linearly from 0 to 1 as ice temperature T increases from -8 C to -5 C, B decreases linearly from 1 to 0 as T increases from -5 C to -3 C, and B is zero at other ice temperatures. N_i is the number of ice particles produced per second, N_{24} is the number of cloud droplets larger than 24 μm in diameter that are collected by ice each second, N_{13} is the number of cloud droplets smaller than 13 μm in diameter that are collected by ice each second.

Ice Crystal Nucleation -- continued

2. Contact nucleation



3. Homogeneous freezing of cloud droplets $T < -30^{\circ}\text{C}$

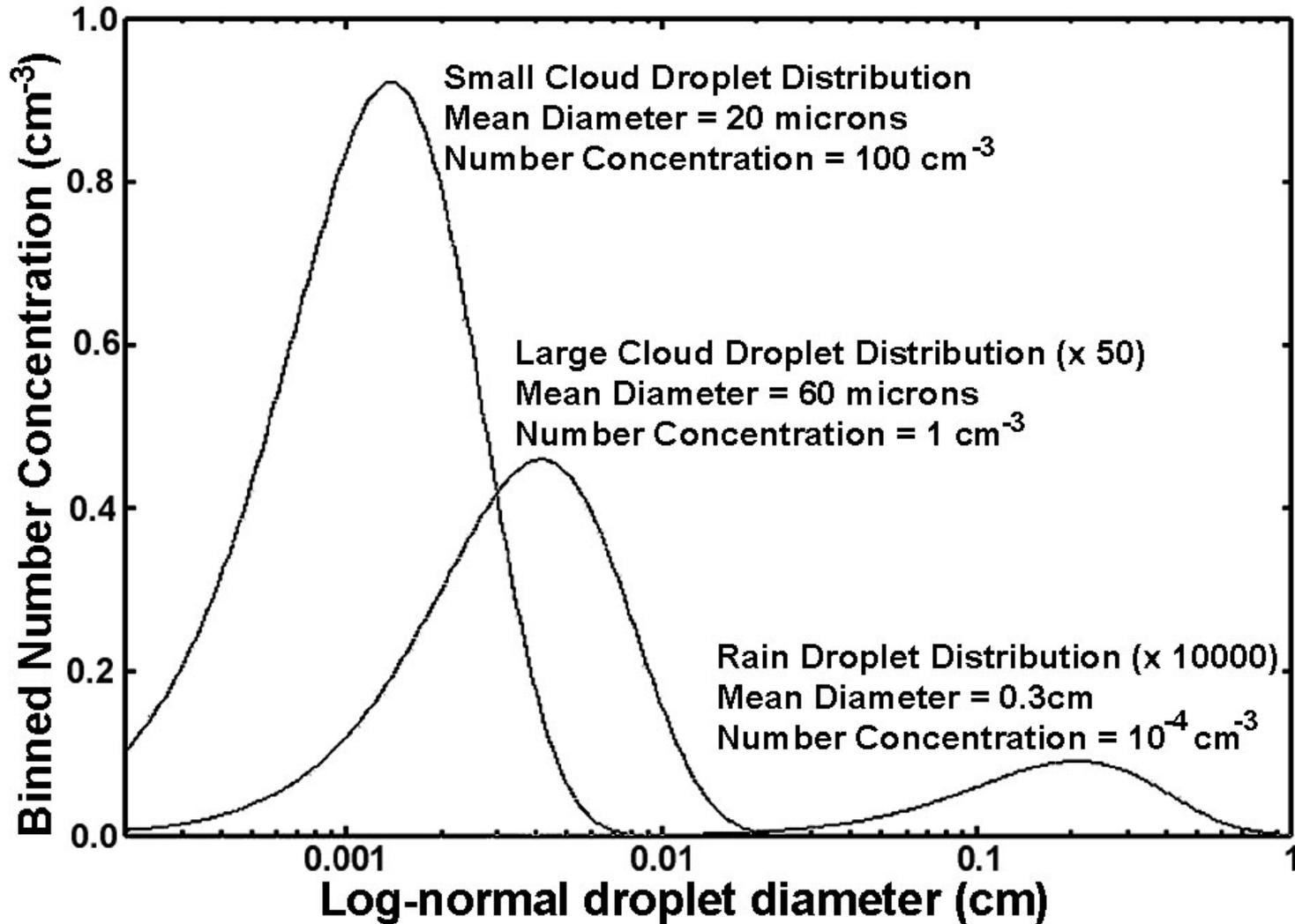
4. Homogeneous freezing of haze

Rate depends on T , r_v , amount of haze present

Microphysical Processes Represented in RAMS

- Cloud droplet nucleation in one or two modes
- Ice nucleation
- Vapor deposition growth
- Evaporation/sublimation
- Heat diffusion
- Freezing/melting
- Shedding
- Sedimentation
- Collisions between hydrometeors
- Secondary ice production

RAMS Liquid Hydrometeor Distributions



Ice Habits

Pristine ice and snow are allowed to have any of five different habits (shapes): columns, needles, dendrites, hexagonal plates, and rosettes. The dependence of mass and of fall velocity on diameter are different for each habit.

Unique Features of RAMS Microphysics:

- Uses generalized gamma distribution basis functions :

$$n(D) = \frac{N_t}{\Gamma(\nu)} \left(\frac{D}{D_n} \right)^{\nu-1} \frac{1}{D_n} \exp\left(-\frac{D}{D_n} \right)$$

where $n(D)$ is the number of particles of diameter D , N_t is the total number of particles, ν is the shape parameter, and D_n is some characteristic diameter of the distribution. The Marshall-Palmer (exponential) and Khrgian-Mazin distribution functions are special cases of this generalized function.

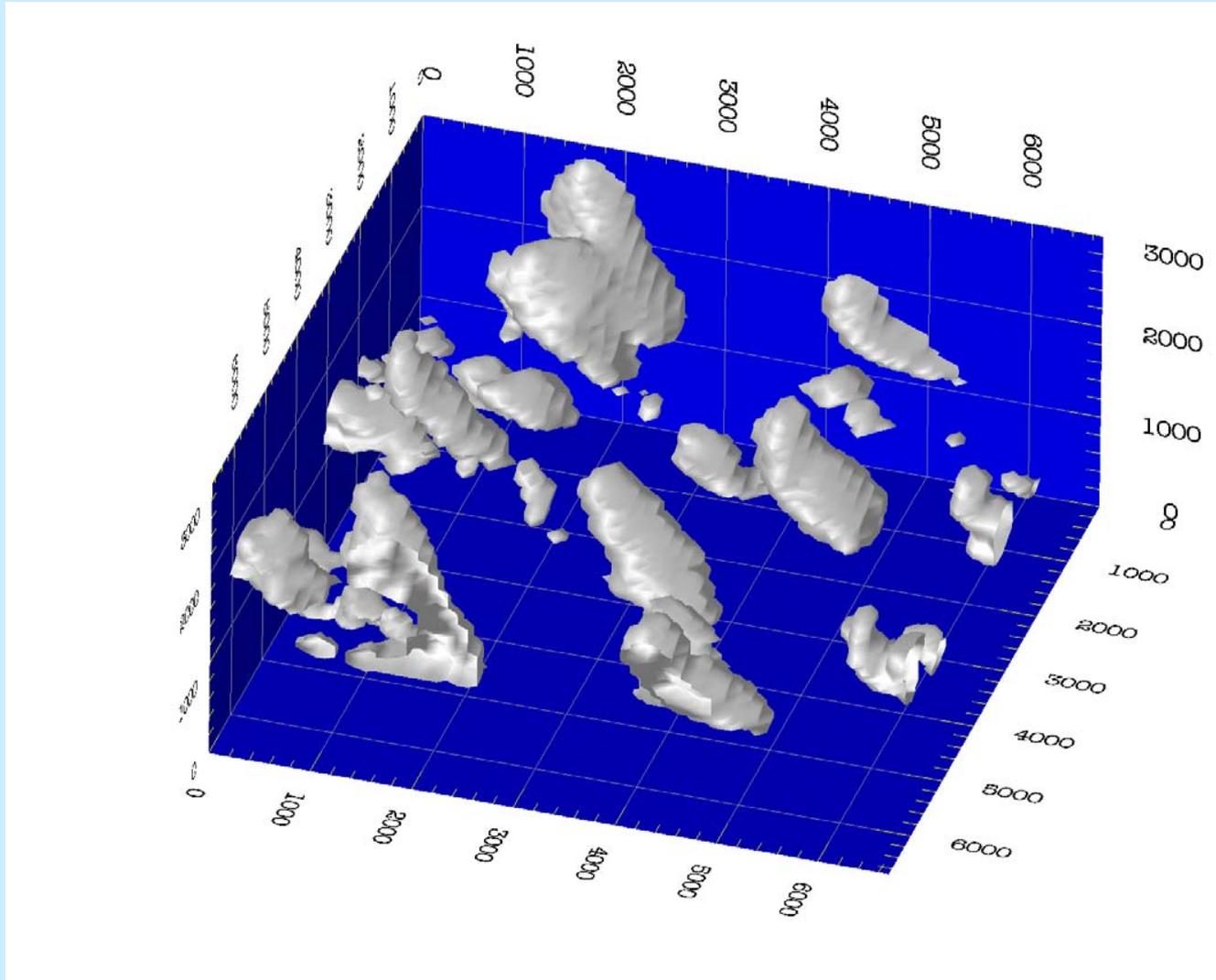
- Simulations can be done with one or two moments. When two-moments of a hydrometeor class is predicted, all that is needed to completely specify the distribution function given by (1) is the specification of ν .

- Collection is simulated using stochastic collection solutions rather than continuous accretion approximations. Owing to the use of look-up tables, it became apparent that it is no longer necessary to constrain the system to constant or average collection efficiencies. Thus the formerly ad hoc auto-conversion formulations in RAMS was replaced with full stochastic collection solutions for self-collection among cloud droplets and for rain (drizzle) drop collection of cloud droplets. This approach has been extended to all hydrometeor interactions.

- The philosophy of bin representation of collection was also extended to calculations of drop sedimentation. Previously, bulk microphysics schemes have treated sedimentation of hydrometeors by integrating over the entire particle size-spectra and obtaining a mass-weighted fall speed. Bin sedimentation is simulated by dividing the gamma distribution into discrete bins and then building look-up tables to calculate how much mass and number in a given grid cell fall into each cell beneath a given level in a given time step.

Boundary Layer Clouds- LES Simulations

PDFs of cumulus clouds



Isosurface of cloud water: 0.001 (g/kg)

Previous research

Twomey (1974) first pointed out that increasing pollution results in greater CCN concentrations and greater numbers of cloud droplets, which, in turn, increase the reflectance of clouds. Subsequently, Twomey (1977) showed that this effect was most influential for optically thin clouds. Estimates suggest that this cooling can be strong enough to partially offset greenhouse gas warming.

Albrecht (1989) hypothesized that the higher droplet concentrations in clouds would reduce the rate of formation of drizzle drops by collision and coalescence. The reduced rate of drizzle formation would result in higher liquid water contents and higher droplet concentrations and lead to longer-lived clouds which by increasing cloud cover would lead to further enhance the albedo of those clouds.

But, this is not the whole story!

Drizzle can have complicated impacts on the marine BL

- Drizzle falling only partway through the sub-cloud layer can destabilize the BL leading to cumulus under stratus.
- Drizzle falling through the entire sub-cloud layer can cool and stabilize the entire BL and lead to decoupling of the stratus layer from the surface.
- Implication: hygroscopic seeding of lightly drizzling clouds could weaken the clouds and reduce precipitation overall.

In Jiang et al's. (2002) LES of marine stratocumulus, higher CCN concentrations suppressed drizzle which resulted in weaker penetrating cumulus and an overall reduction in the water content of the clouds. Thus cloud albedo was very little influenced by the increase in CCN concentrations.

Additional studies:

- Ackerman et al. (2004) also showed that increases in CCN do not necessarily result in increases in LWP in stratocumulus clouds. A primary factor affecting the LWP response to aerosol changes is the profile of humidity above the inversion. Only when the humidity above the inversion was high did increases in aerosol result in an increase in LWP. When dry air overlies the inversion, increases in aerosol tend to decrease LWP because of enhanced entrainment drying. Similar results were obtained by Lu and Seinfeld (2005).

Aerosol Influences on entrainment in cu

- **Another example of departures from the Albrecht hypothesis is Xue and Feingold's simulations of aerosol influences on tradewind cumulus.**
- **They found that increasing concentrations of CCN and droplets, produced smaller droplets and suppressed drizzle and led to enhanced evaporation of droplets by entrainment.**
- **Because, for a given LWC, smaller droplets evaporate more readily than larger droplets, entrainment induced evaporative cooling was enhanced when CCN concentrations were high, which led to greater entrainment rates, reduced cloud fraction, cloud size, and cloud depth.**

- These simulations highlight the nonlinearity of cloud systems when drizzle is present and suggests that increased concentrations of CCN may not always increase cloud water contents, cloud lifetimes, and cloud albedo.

GCCN and Drizzle

- Giant and ultra-giant nuclei are particles greater than 5 micrometers in diameter that are at least wettable.
- They are not measured with normal CCN thermal-gradient cloud chambers.
- Typical concentrations over the ocean range from 10^{-4} to 10^{-2} cm^{-3} .

Sources of GCCN

- Sea salt is a good GCCN and thus marine clouds forming at high winds will be rich in GCCN concentrations.
- Desert dust if mixed with sulfate laden pollutants or traveling over the sea for long periods become coated with sulfates and serve as GCCN.
- Diesel emissions, and dust-related human activities (construction, poor agriculture practices) can be good sources of GCCN.

LES by Feingold et al. (1999) found:

- GCCN has little influence in clouds where CCN concentrations are low, say about 50 cm^{-3} where drizzle is very active.
- At higher CCN concentrations where drizzle is suppressed, high GCCN concentrations can enhance drizzle.
- Thus GCCN can moderate the impact of anthropogenic emissions of CCN. One can expect to find polluted clouds raining vigorously if many GCCN are present

Summary

- The CCN albedo hypothesis is much more complicated than originally envisioned by Twomey or Albrecht's extension of that concept to suppressing drizzle.
- Drizzle can have important nonlinear feedbacks on the cloudy boundary layer.
- CCN is not the only aerosol important to cloud albedo; concentration variability of GCCN can have important feedbacks.
- GCMs are unable to simulate the drizzle process, its dependence on GCCN concentrations and complicated feedbacks illustrated here.

Pollution Impacts on orographic cloud precipitation

Winter Orographic Simulation Configuration

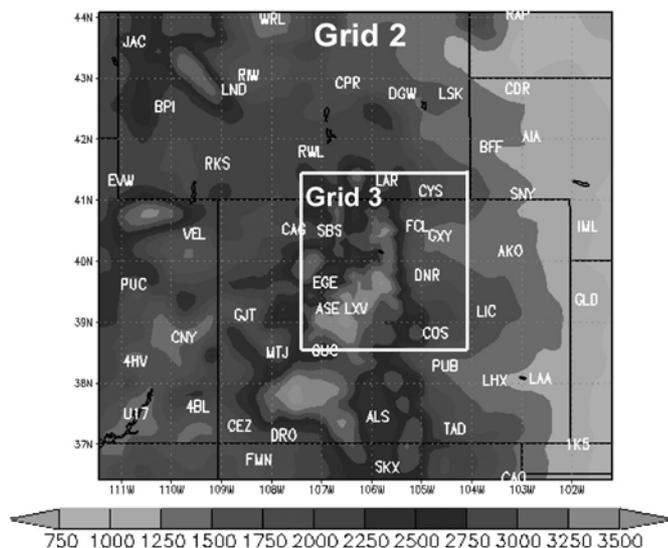
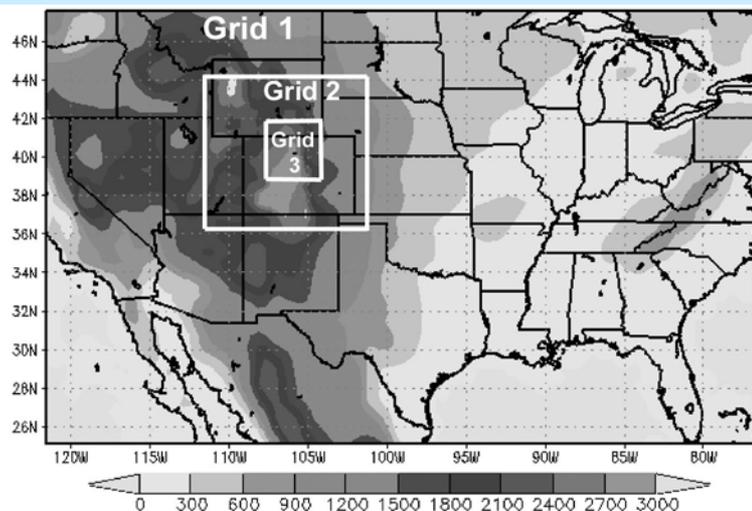


Fig. 1. Realtime RAMS model grid configuration displaying the outer and nested grids (top), and a zoomed display of the two inner grids and their boundaries relative to local cities in Colorado and surrounding states (bottom). Topography (m) is overlaid.

**Run Time: February 28, 2004 0000Z
for 39 hours.**

Three grid configuration with:

Grid 1: $Dx = Dy = 48\text{km}$

Grid 2: $Dx = Dy = 12\text{km}$

Grid 3: $Dx = Dy = 3\text{km}$

DZ minimum = 300m

DZ maximum = 750m

Two-moment microphysics

Harrington 2-Stream Radiation

Kuo Cu-Parm on Grid 1

K-F Cu-Parm on Grid 2

No Cu-Parm on Grid 3

**Lateral boundary nudging with
Eta Forecast Grids**

Summary:

- **Saleeby and Cotton's (2005) simulation of wintertime orographic clouds revealed:**
 - **At higher concentrations of CCN, the average cloud droplet size decreases.**
 - **Smaller supercooled droplets more readily evaporate in the presence of a strong Bergeron process.**
 - **LWC is reduced at higher CCN concentrations.**
 - **Thus at high CCN concentrations not only is riming reduced by lower collection efficiencies for smaller droplets but so is LWC, further reducing riming and precipitation.**

Pollution Impacts on Arctic Stratus Clouds

What is the impact of aerosol entrainment from the above the inversion on the structure of Arctic boundary layer clouds and on sea-ice thickness?

THE COUPLED MODEL

- RAMS was coupled to the Los Alamos CICE model.

SIMULATIONS

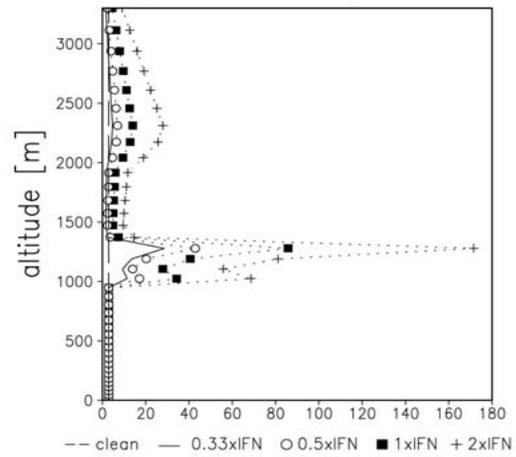
Three-month CRM simulations for the melting season (1 May-31 July 1998), using 4 May observed aerosol profiles as benchmarks.

Six-month CRM simulations for the freezing season (16 Oct 1997- 16 Apr 1998).

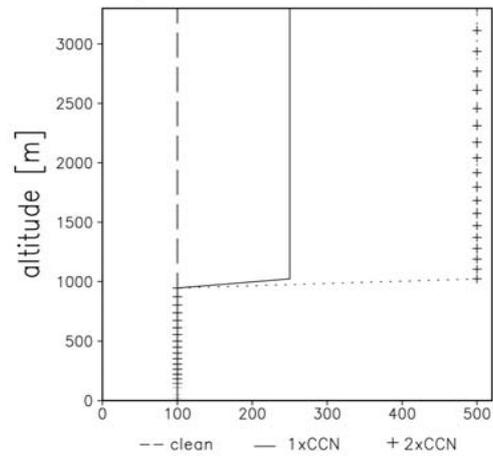
MELTING SEASON MULTIMONTH SIMULATIONS

- Domain: 5X4 Km, $\Delta x = 50\text{m}$, $\Delta z = 30\text{m}$, $\Delta t = 2$ sec.
- Simulation time: 92 days from 1 May 1998.
- Cyclic boundary conditions and nudging using 2-3 daily SHEBA soundings.
- Two-moment microphysics.
- Sub-grid thickness distribution: six categories with a linear remapping scheme (Lipscomb, 2001).
- Initial mean thickness of the distribution: 2.41m. (Average of seven closest gauges for 1 May.)

a) Initial IFN profiles



b) Initial CCN profiles



SUMMARY

- Results indicate that increasing IN concentrations within the upper layer:
 - increases total condensate path,
 - decreases the liquid water fraction,
 - decreases the relative importance of ice sedimentation by reducing their free fall speed,
 - increases net radiative forcing,
 - enhances sea-ice melting rates when mixed phase clouds are present.
- Results suggest that CCN entrainment has an opposite although less important effect.
- Six-month cloud resolving simulations results suggest lower freezing rates for more polluted aerosol profiles above the inversion.

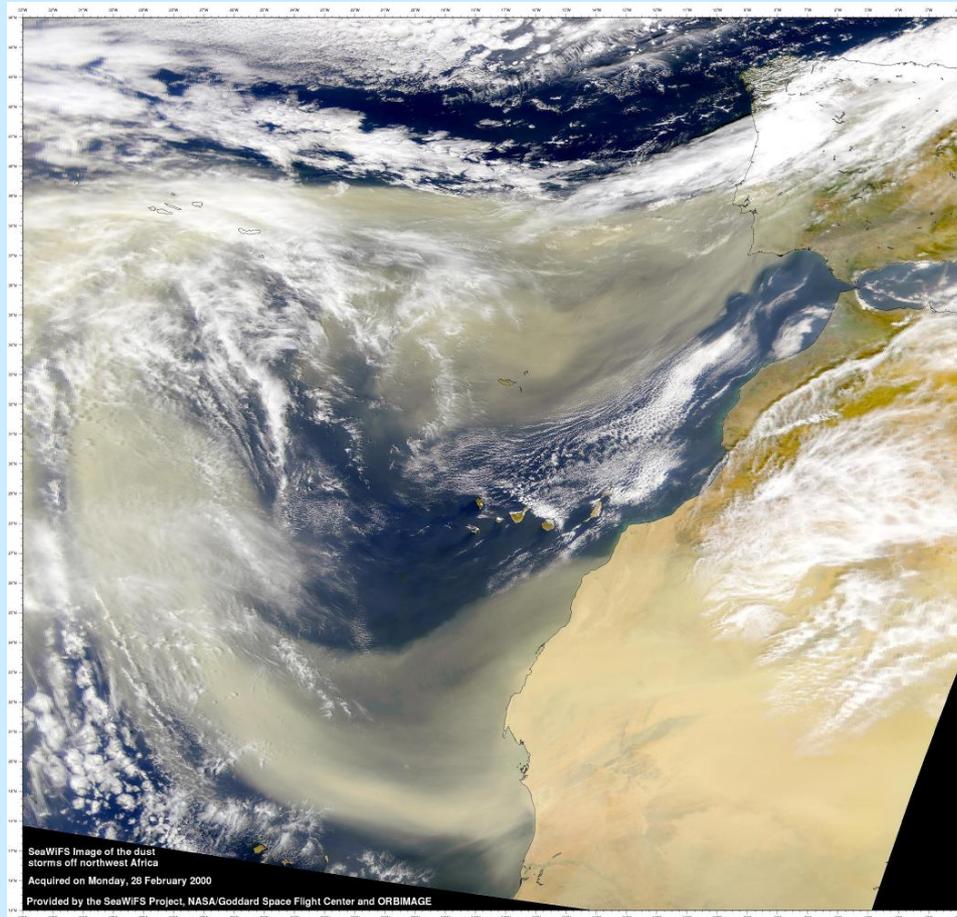
Aerosol Pollution Impacts on Deep Convective Clouds and Precipitation

Previous Research

- *Seifert and Beheng* [2006b] showed that the effect of changes in CCN on mixed phase convective clouds is quite dependent on cloud type.
- They found that for small convective storms, an increase in CCN decreases precipitation and the maximum updraft velocities.
- For multicellular storms, the increase in CCN has the opposite effect – namely, promoting secondary convection, and increasing maximum updrafts and total precipitation. Supercell storms were the least sensitive to CCN.
- Their study also showed that the most important pathway for feedbacks from microphysics to dynamics is via the release of latent heat of freezing.

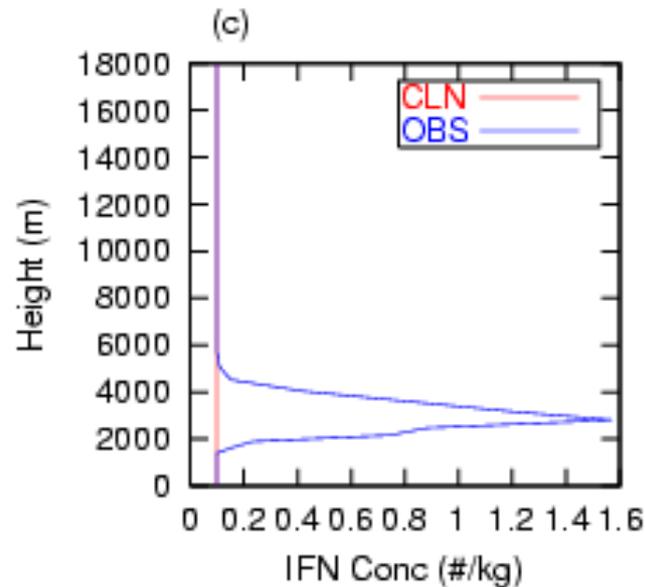
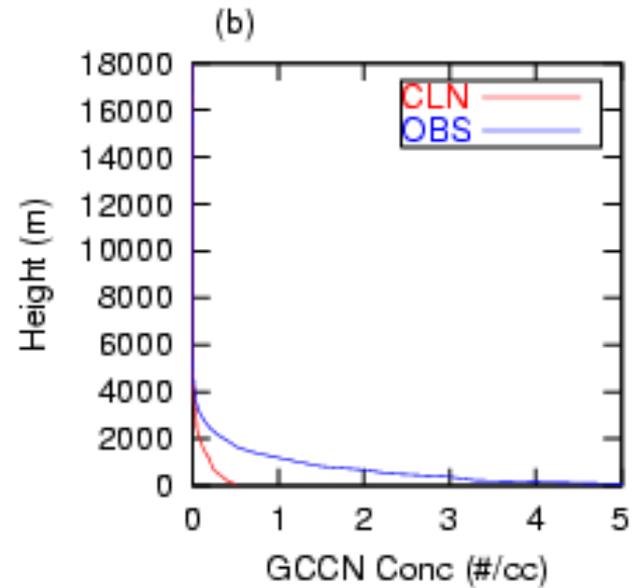
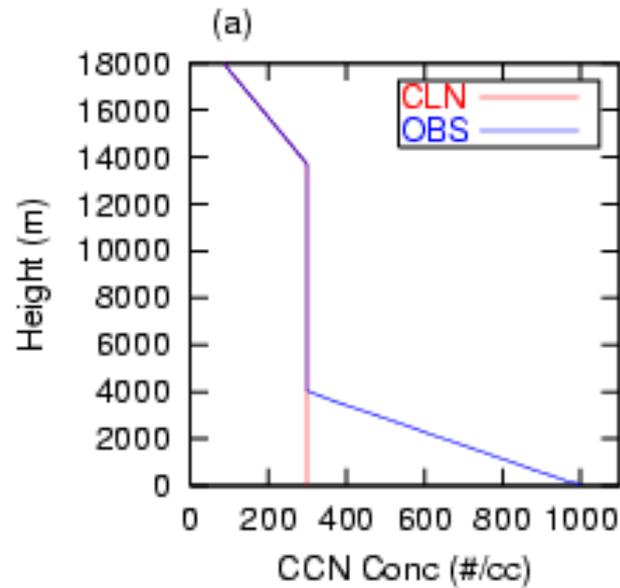
- Other modeling efforts by *Lynn et al.* [2005a,b], *Khain et al.* [2005] show complex dynamical responses to aerosols sometimes leading to greater precipitation amounts and other times less

Simulations of Florida Thunderstorms during a Saharan Dust Event over South Florida

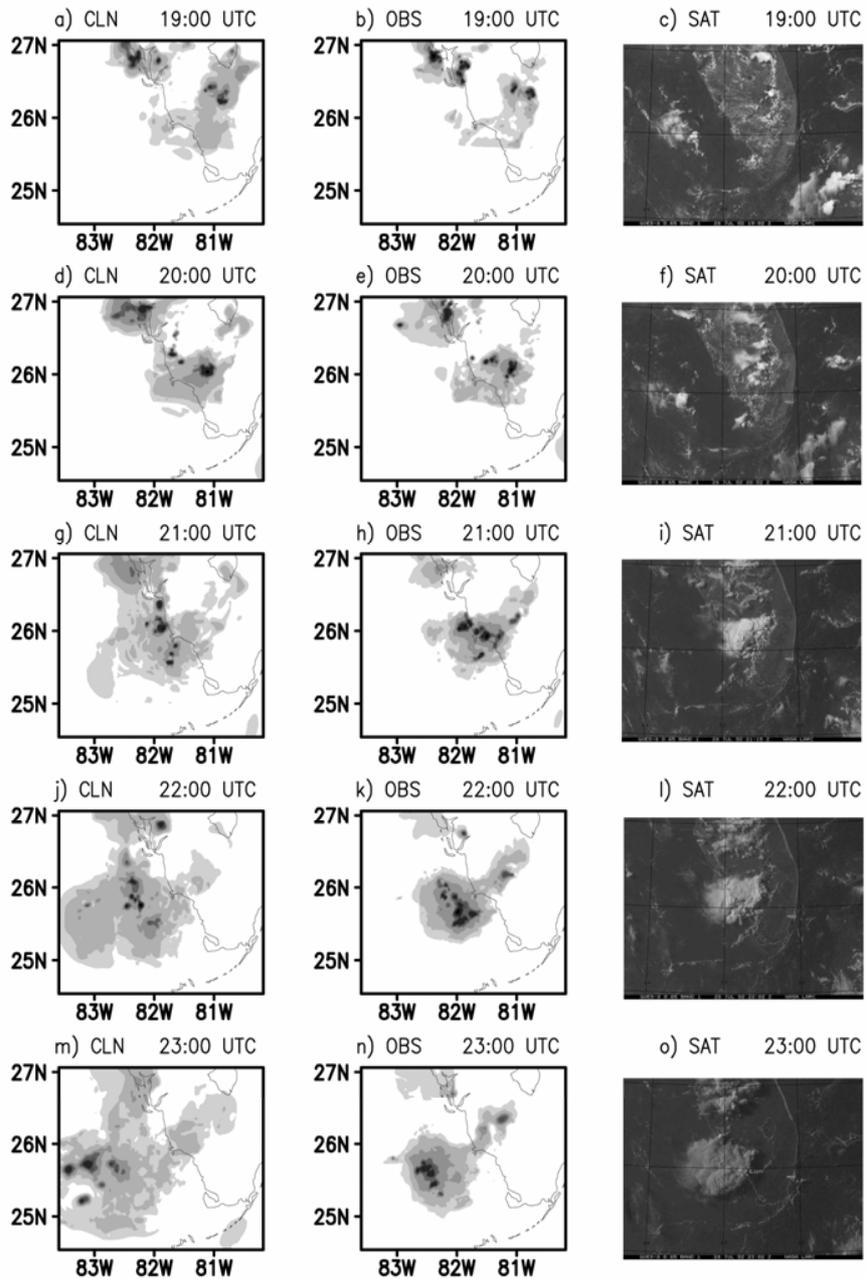


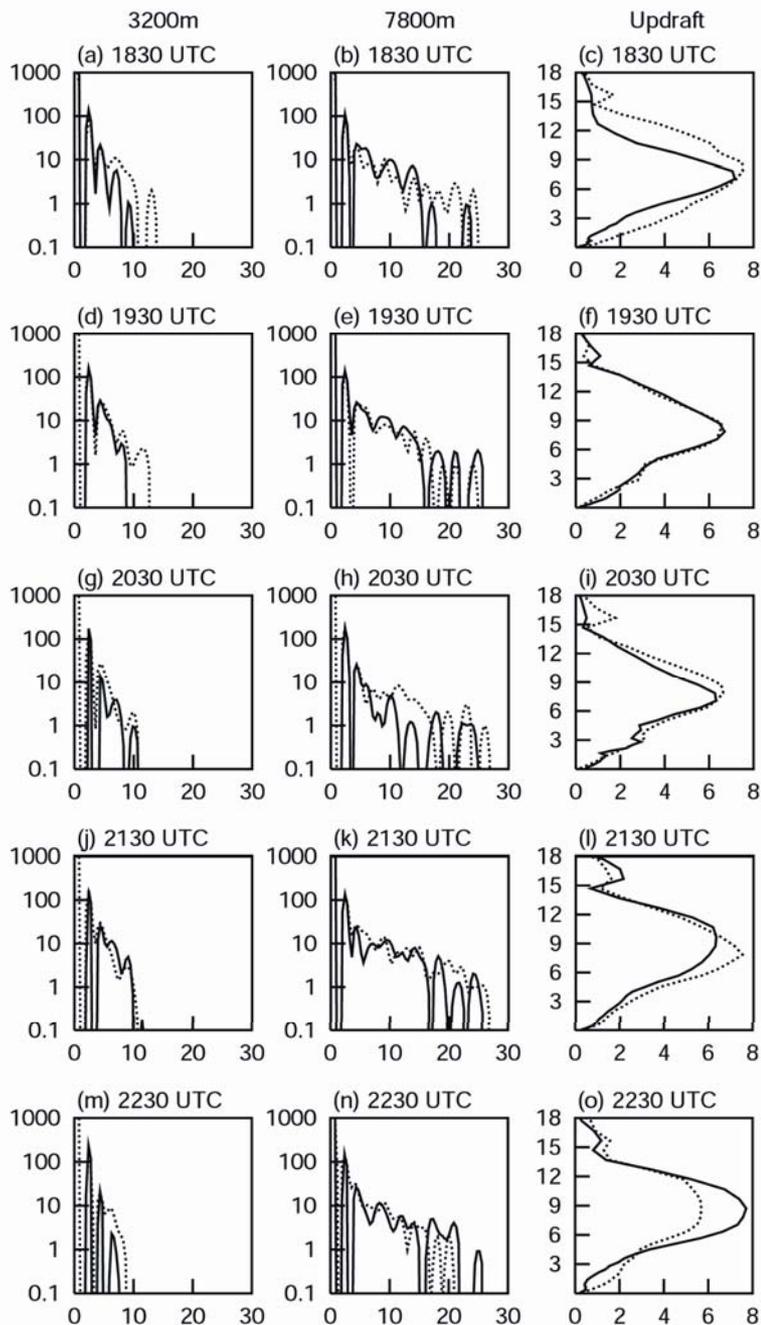
Based on van den Heever et al., 2006

- **Simulations are cloud-resolving mesoscale runs for a 12h period that includes sea-breeze forcing of convection.**
- **Finest grid spacing is 500m.**
- **Simulations are performed for clean background, and then enhanced CCN, GCCN, IFN concentrations individually and then all (observed).**



“Clean” and
“observed” vertical
(a) CCN, (b) GCCN,
and (c) IN profiles
used to initialize
RAMS





Density distribution of vertical velocity at ~3200m AGL (left column) and ~7800m AGL (middle column), and the horizontally averaged velocities within the updraft (right column) for the CLN (solid lines) and OBS (dotted lines) cases at hourly intervals starting at 1830 UTC. Abscissa is vertical velocity, and ordinate is number (on a log scale) for the density distributions and height (km) for the averaged velocities.

RANK	RUN	Volumetric Precipitation (acre-feet)
1	IN	66608
2	GCCN	65874
3	GCCN+IN	63487
4	CLN	63289
5	CCN	61741
6	CCN+GCCN	58275
7	IN+CCN	57700
8	OBS	57008

Volumetric Precipitation at 1800 UTC

RANK	FACTOR	Volumetric Precipitation (acre-feet)
1	CLN	442168
2	Interactions between CCN and IN	368053
3	Interactions between GCCN and IN	352112
4	Interactions between CCN and GCCN	349373
5	Interactions between CCN, GCCN and IN- (observed)	346309
6	GCCN	344338
7	IN	330610
8	CCN	327560

Factor Analysis of Volumetric Precipitation at 0000 UTC

CRYSTAL-FACE Results

- Variations in the concentrations of nucleating aerosol – significant impact on:
 - Microphysical characteristics.
 - Dynamical characteristics.
 - Accumulated surface precipitation.

CRYSTAL-FACE Results

- Dynamical Characteristics:
 - updrafts are consistently stronger and more numerous in the dust case
 - driven by the latent heat release due to freezing of larger amounts of supercooled water associated with higher aerosol concentrations within the storm.

CRYSTAL-FACE Results

- Impacts of GCCN and IN concentration variations are just as significant as those associated with CCN.
- All three nucleating aerosols affect the depth, microphysical characteristics, water mass and organization of the anvil

Urban aerosol influences—
METROMEX revisited
based on van den Heever and
Cotton(2007)

Experiment Design

- In the CONTROL experiment, RAMS is initialized homogeneously with rural CCN and GCCN concentrations.
- In the sensitivity tests, a continuous source of urban CCN and / or GCCN concentrations are used within the lowest 500m over the urban region. The sensitivity tests are otherwise identical to the CONTROL experiment.
- These experiments were repeated in which the urban region was removed while the aerosol characteristics were maintained.

AEROSOL CONCENTRATIONS

- High background:

Rural: CCN: 1200 cc^{-1} ; GCCN: 0.1 cc^{-1}

Urban: CCN: 2000 cc^{-1} ; GCCN: 0.2 cc^{-1}

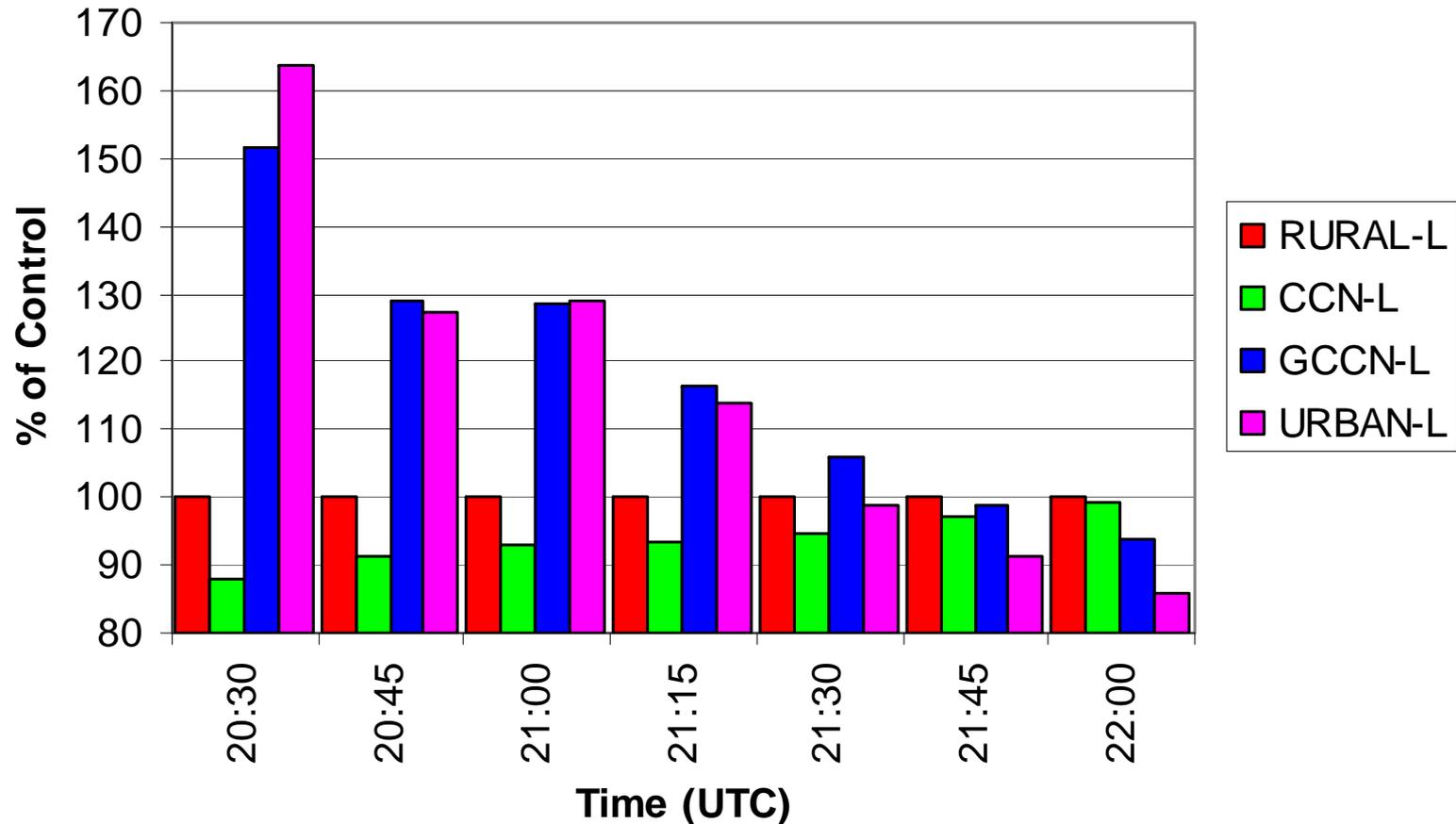
- Low background:

Rural: CCN: 800 cc^{-1} ; GCCN: 0.01 cc^{-1}

Urban: CCN: 2000 cc^{-1} ; GCCN: 0.2 cc^{-1}

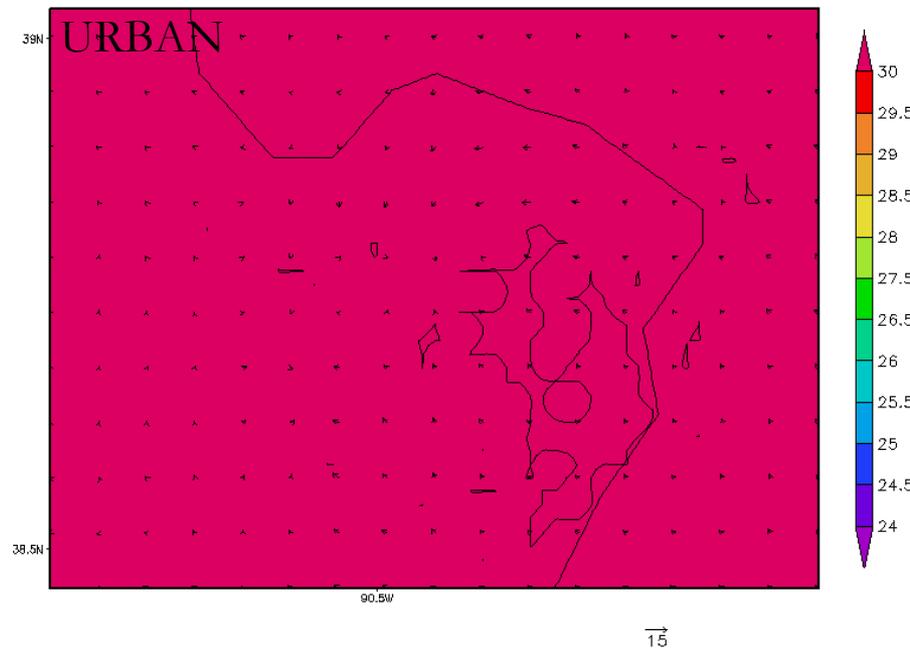
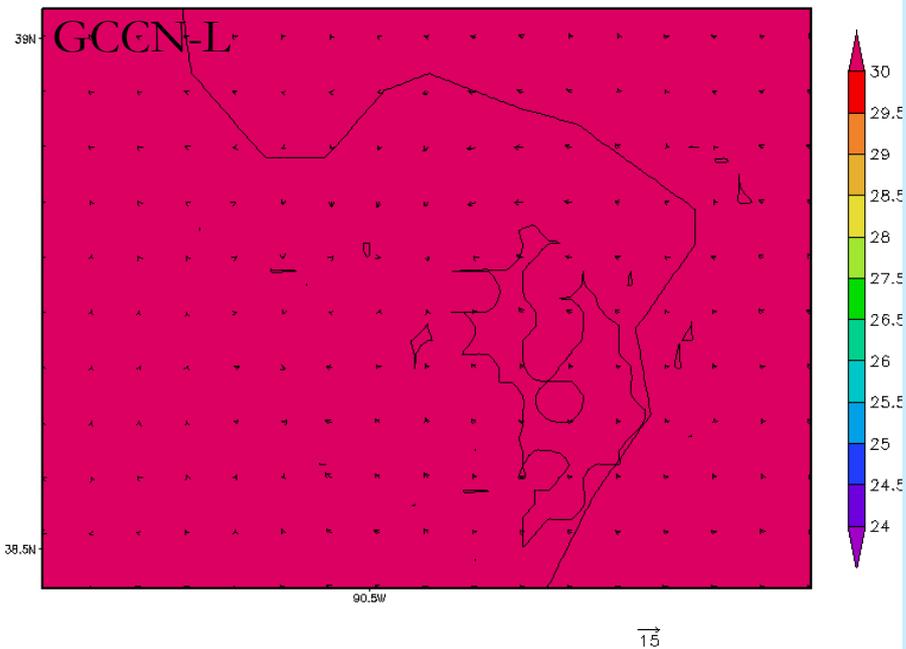
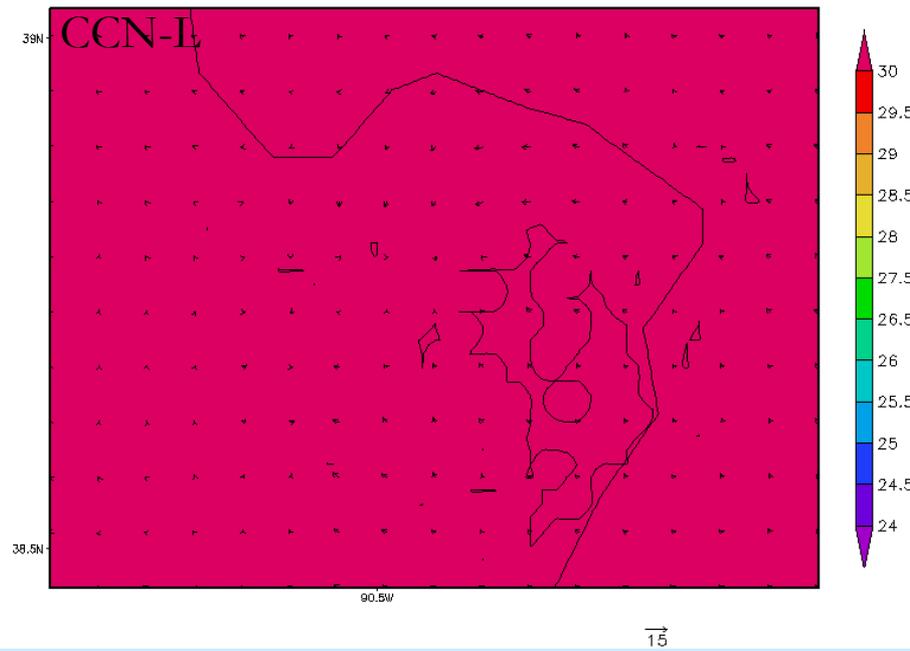
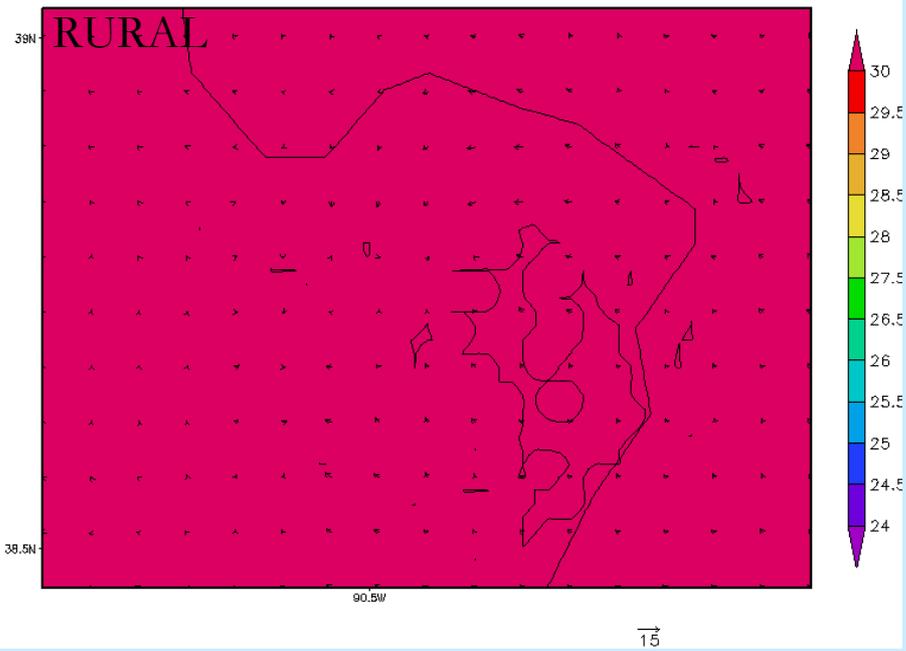
Downwind Precipitation Low Background Concentrations

Accumulated Precipitation as % of the Control (RURAL-L) -
Low Background Concentrations



Accumulated Volumetric Precipitation (acre-feet) for entire Grid 3

Time	Rural	CCN	GCCN	Urban
20:00	0	0	0	0
21:00	13956	13748	14411	14490
22:00	36338	35900	35173	35299
23:00	63409	63964	61451	58227
00:00	74370	75499	72511	69914



Summary of deep convection simulations

- **Urban land-use has the biggest control on locations and amounts of precipitation**
- **Overall both CCN and GCCN concentrations are important to cloud responses to varying aerosols.**
- **For deep convective clouds the nonlinear interactions between varying aerosol amounts and cloud dynamics can lead to responses in terms of rainfall amounts that are quite unpredictable. Short term responses may increase rainfall whereas longer-term responses can decrease rainfall.**

Impacts of Dust in the SAL as CCN on the Evolution of an Idealized Tropical Cyclone

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It is hypothesized that the SAL tend to suppress TC activity by:

(1) Introducing hot and dry air into the storm

(2) Increasing vertical wind shear

(Dunion and Velden 2004)

What is the impact of desert dust particles in the SAL acting as CCN on the development of TCs?

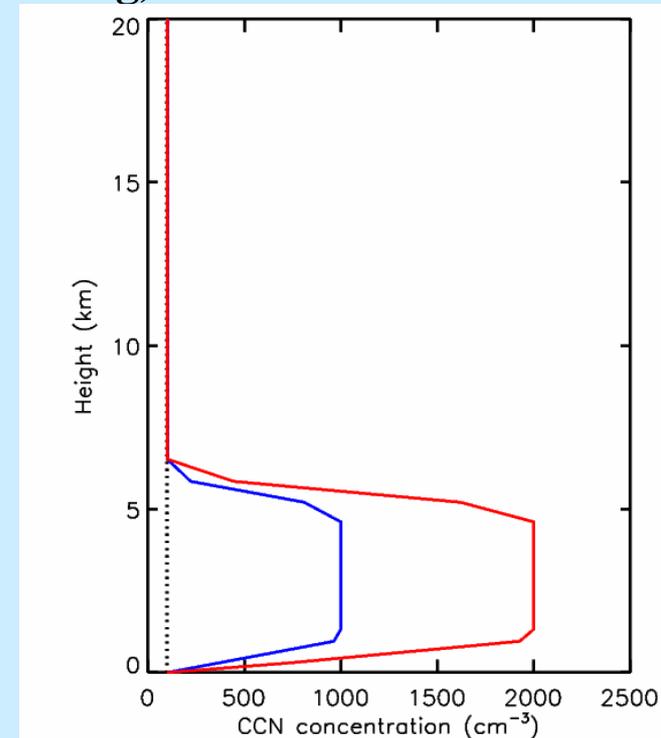
Model setup

- * **Regional Atmospheric Modeling System (RAMS) version 4.3** developed at CSU was used.
 - * **Model was initialized with an axisymmetric MCV (Montgomery et al., 2006).**
 - * **Two-moment microphysics scheme (Saleeby and Cotton, 2004)**
 - * **3 domains with the finest horizontal resolution 2 km**
 - * **SST = 29°C *Simulation time = 72 hours *No environmental winds**
 - * **Mean Atlantic hurricane season sounding (Jordan sounding) initialized the model.**
- **CCN concentration was varied from 100, to 1000 and 2000 cm^{-3} between 1 and 5 km, where dust is typically found.**

Clean – 100 cm^{-3}

Polluted – 1000 cm^{-3}

Double – 2000 cm^{-3}



Discussion

Dunjon and Velden (2004)

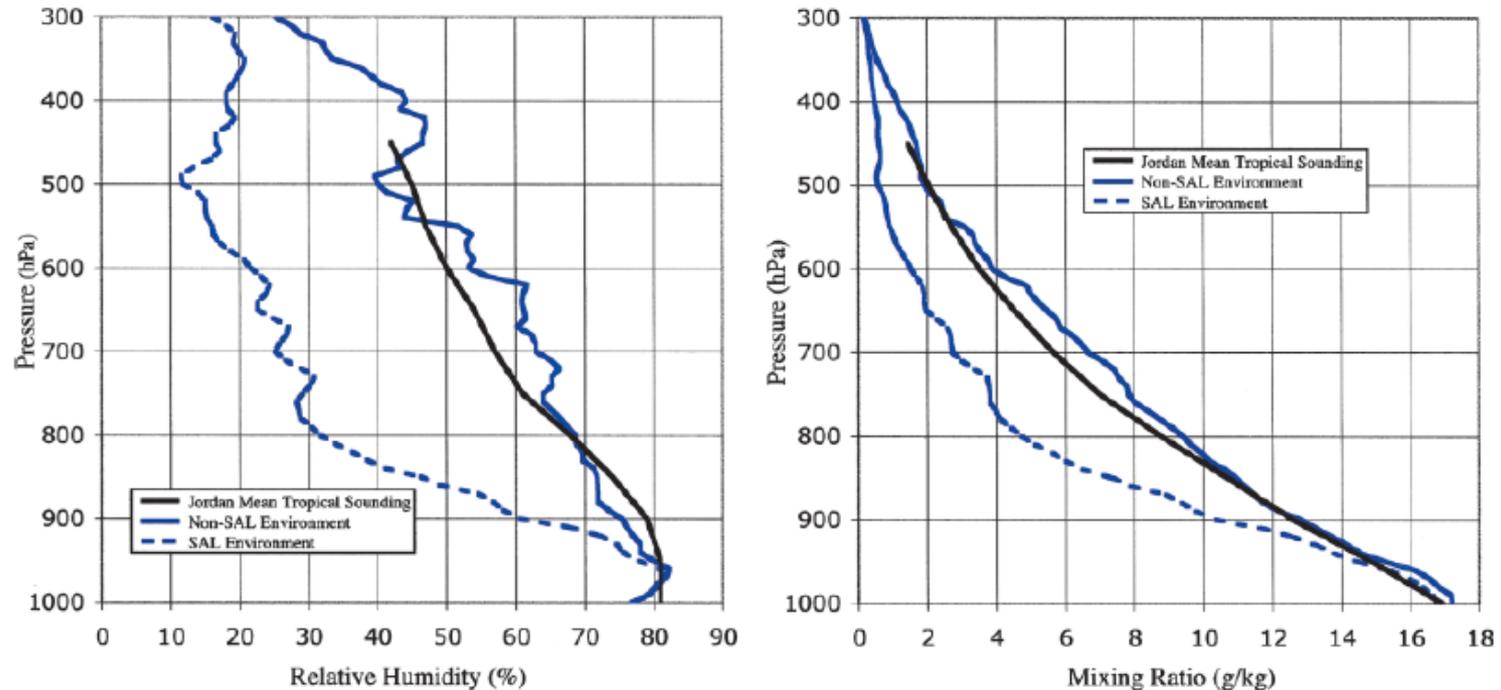
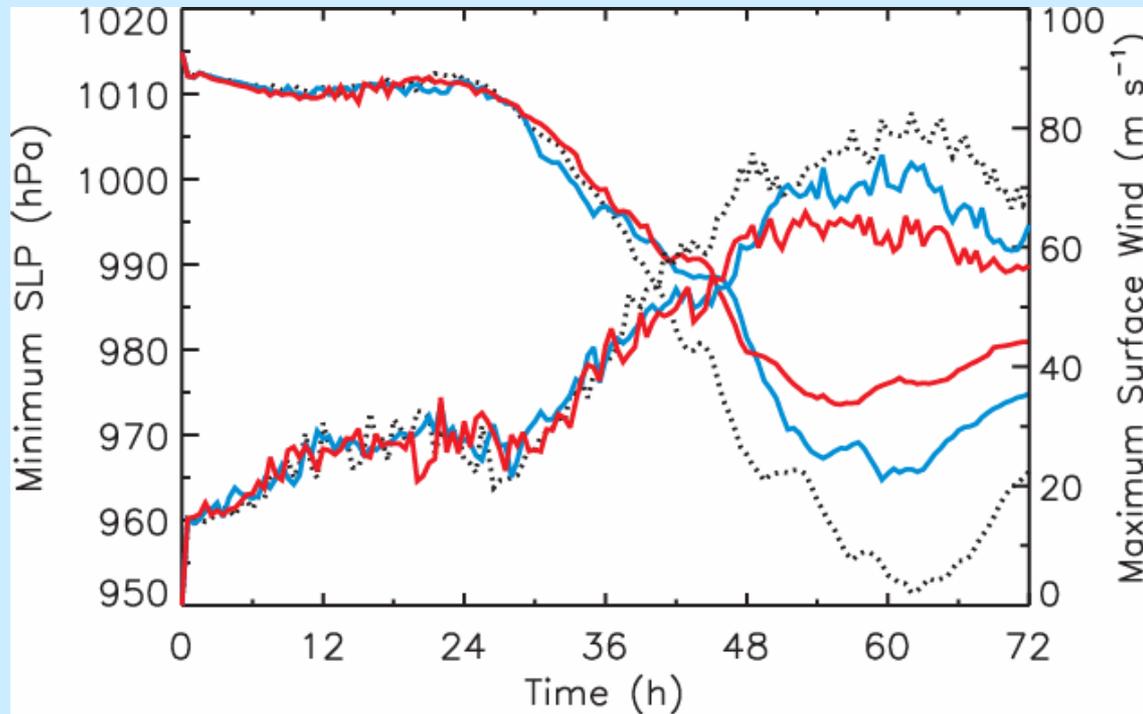


FIG. 2. Composite GPS sonde profiles from sondes launched in the environments of Hurricanes Danielle and Georges of 1998 and Hurricanes Debby and Joyce of 2000. SAL and non-SAL environments were determined using GOES SAL-tracking imagery (see, e.g., Fig. 1). The Jordan mean tropical sounding for the area of the West Indies for Jul–Oct is presented for reference.

Jordan sounding lies between the SAL and non-SAL soundings. Therefore, it is used to depict the transition zone between the SAL and non-SAL environment.

- CCN is horizontally homogeneous.
"Clean" has $100/\text{cm}^3$ from surface to 25km.
- "Polluted" enhanced the CCN in 1km-5km to $1000/\text{cm}^3$.
- "Double" has CCN of $2000/\text{cm}^3$ in 1-5km.

Impacts on storm intensity



Clean – 100 cm⁻³

Polluted – 1000 cm⁻³

Double – 2000 cm⁻³

Simulated storm intensity decreased with increasing CCN concentration.

Impacts on surface radar reflectivity

Increasing CCN \rightarrow Bigger eye; Wider eyewall with less area of heavy rain

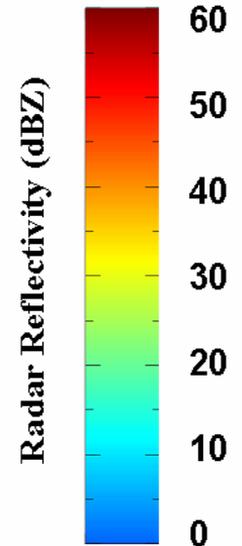
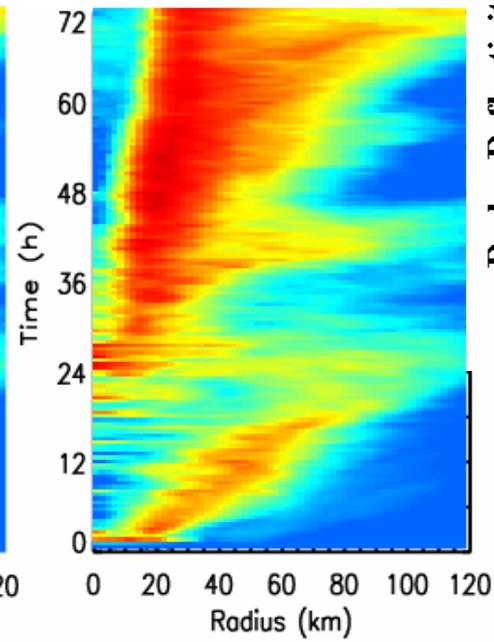
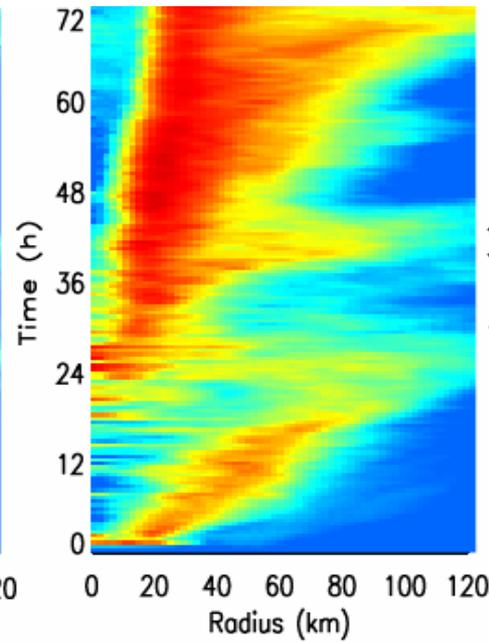
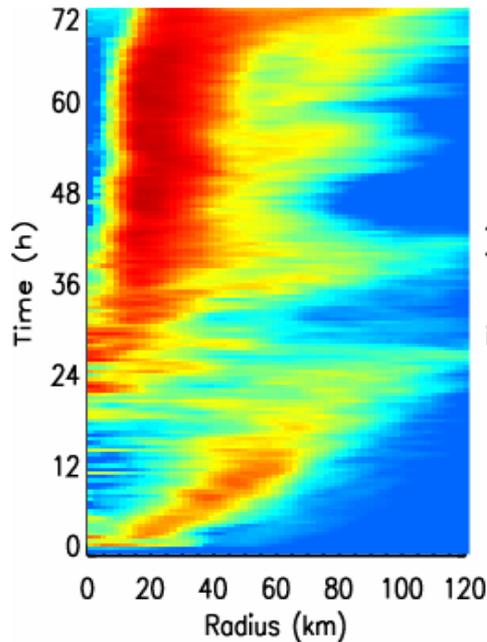
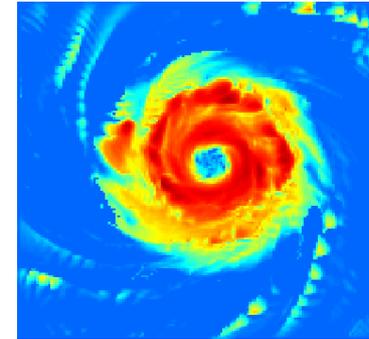
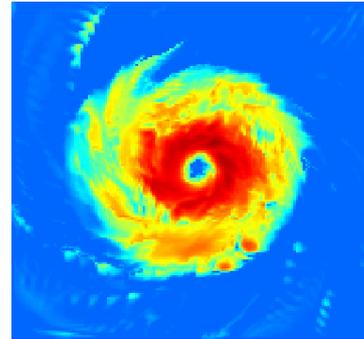
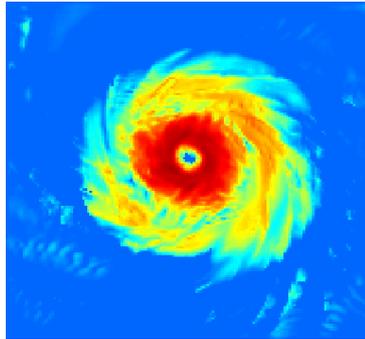
At 60hr

Clean

Polluted

Double

300 km



(a)

(b)

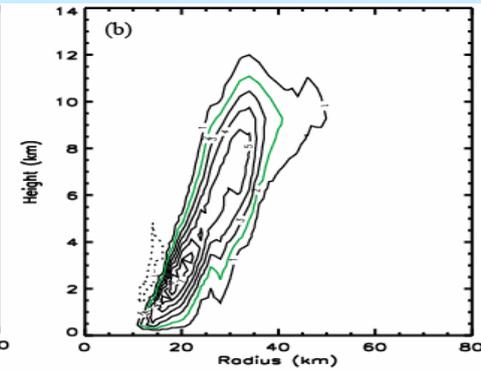
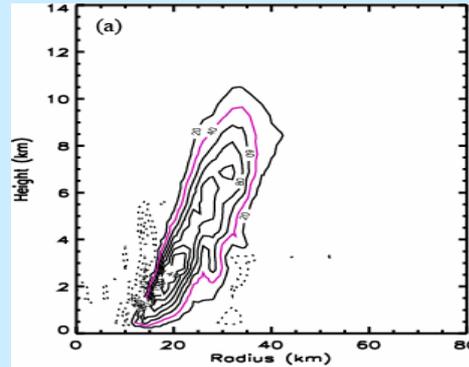
(c)

Impacts on diabatic heating rate

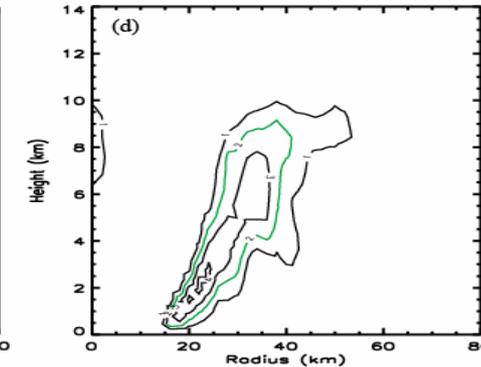
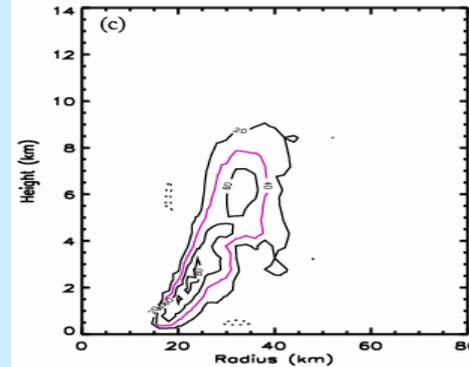
diabatic heating (K/hr)

w (m/s)

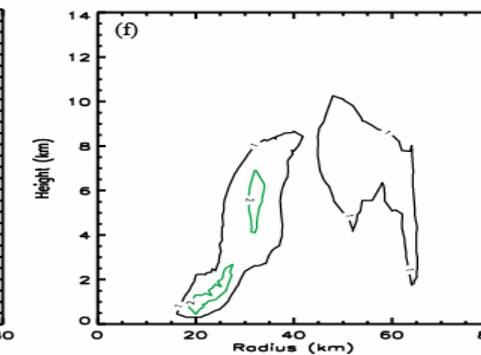
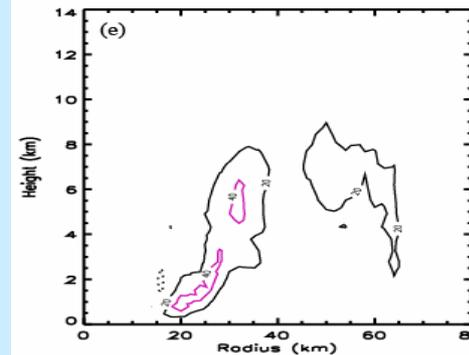
Clean had the highest diabatic heating/cooling rate and produced the strongest updrafts. Strong updrafts were collocated with high diabatic heating rate.



Clean

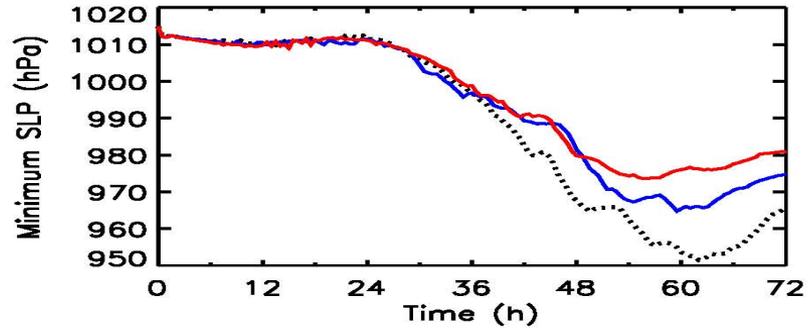


Polluted

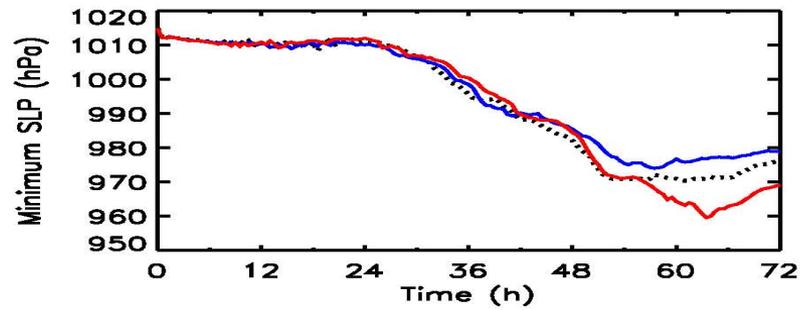


Double

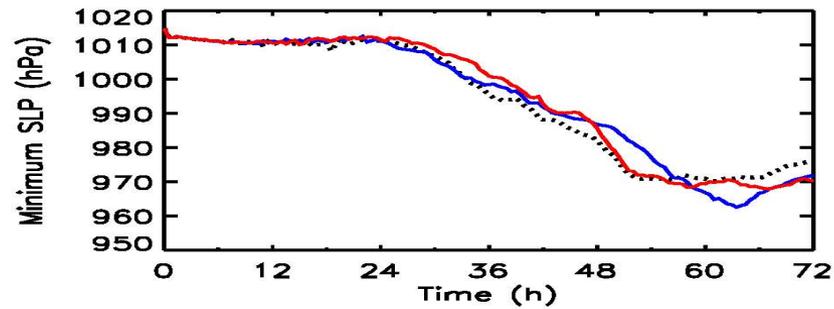
Storm Response to dust acting as GCCN and IN



Dotted: clean CCN; Blue: Polluted CCN; Red: Double Polluted CCN



Dotted: clean GCCN; Blue: Polluted GCCN; Red: Double Polluted GCCN



Dotted: clean IN; Blue: Polluted IN; Red: Double Polluted IN

- The model is not very sensitive to dust serving as IN and when it serves as GCCN the response is not monotonic to increasing GCCN concentrations

Discussion

- (1) Increasing the background CCN concentration from 100 to 1000 and 2000 cm^{-3} between 1 and 5 km led to increases in total activated CCN number, total cloud droplet number, averaged cloud LWP, cloud to rain ratio, and a decrease in cloud droplet mean diameter for the simulations presented here.

Discussion

(2) By changing the ambient CCN concentration, differences in simulated vertical profiles of latent heating rate for diffusional growth of cloud, freezing of raindrops, melting of ice hydrometeors and evaporation of liquid hydrometeors were noted. The corresponding changes in microphysical processes ultimately modified the total latent heating and cooling distribution. Collocation of stronger updrafts and positive heating were found.

Discussion

- (3) The total precipitation reaching ground during the 72 hours are 1.38 , 1.46 and $1.44 \times 10^{10} \text{ m}^3$ for “Clean”, “Polluted” and “Double” case respectively. The difference between simulations is less than 5 %.

Although “Clean” is the strongest storm and has the maximum area of heavy rain, it yielded the least total amount of rain.

Should we consider polluting hurricanes to reduce their intensity?

This would require:

- The development of generators or flares which produce high volumes of small hygroscopic aerosol.
- Additional simulations in which actual aircraft flights are emulated releasing small CCN into idealized storms.
- Further seeding simulations for actual storms like Katrina.
- Field experiments in which small-aerosol CCN seeding is performed in hurricanes well-removed from land-fall to examine if the predicted changes in precipitation, vertical velocity, along with storm intensity can be actually achieved.

Conclusions

- The response of even simple clouds like stratocumuli and cumuli to varying amounts of cloud nucleating aerosol can be quite nonlinear
- The clouds most susceptible to pollution influences on precipitation are orographic clouds and perhaps high latitude stratus clouds
- Deep convective storms including tropical cyclones are quite sensitive to varying concentrations of cloud nucleating aerosols (CCN, GCCN, IN). The response, however, is, not surprisingly, very nonlinear and depends on the large scale forcing, stability, shear, and scales of convection.