Aerosol Influences on Deep Convective Clouds and Storms

William R. Cotton
Dept. of Atmospheric Science
Colorado State University
Fort Collins, CO 80526

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):

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

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

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

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

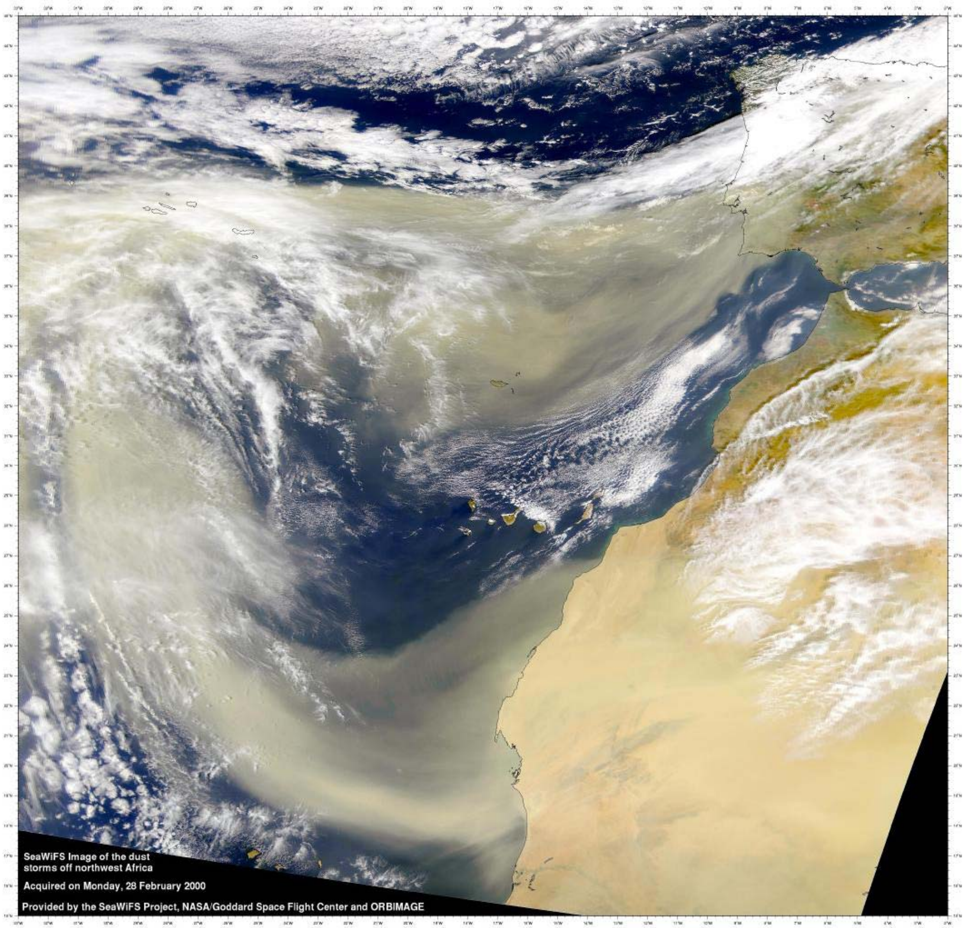
where B increases linearly from 0 to 1 as ice temperature T increases from -8 C to -5 C, B decreases linearly from 1 to 0 as T increases from -5 C to -3 C, and B is zero at other ice temperatures. Ni is the number of ice particles produced per second, N24 is the number of cloud droplets larger than 24 ❍m in diameter that are collected by ice each second, N_{13} is the number of cloud droplets smaller than 13❍m in diameter that are collected by ice each second.

Aerosol Influence on deep convective clouds

- *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.

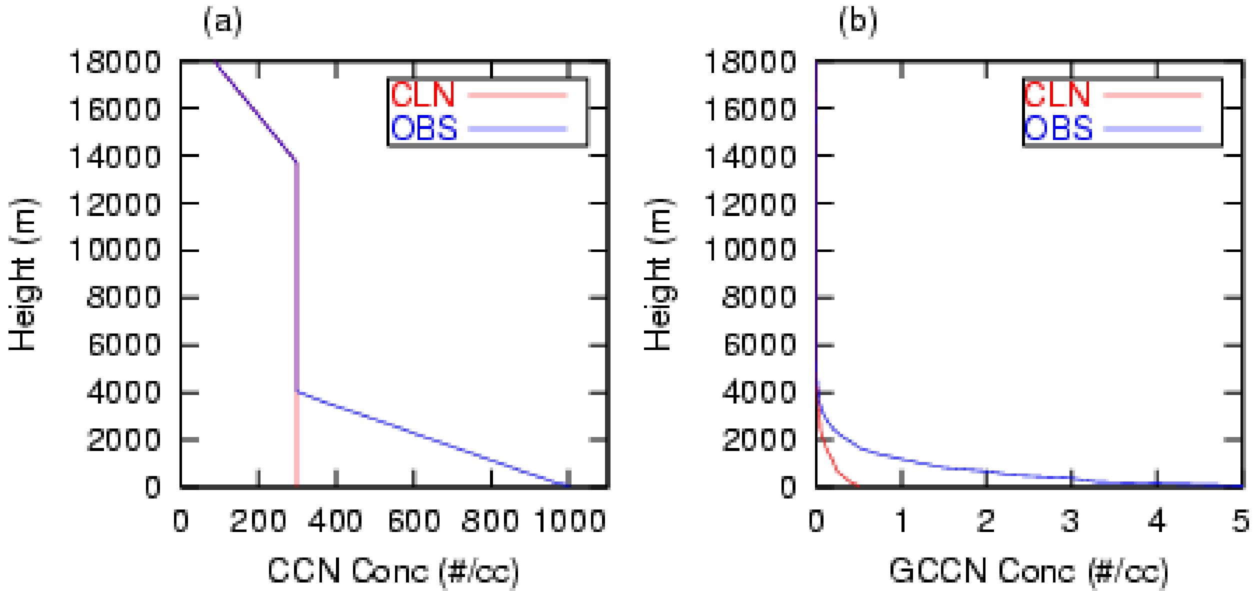
- Modeling efforts by *Lynn et al*. [2005a,b], *Khain et al.* [2005] show complex dynamical responses to aerosols sometimes leading to greater precipitation amounts and other times less

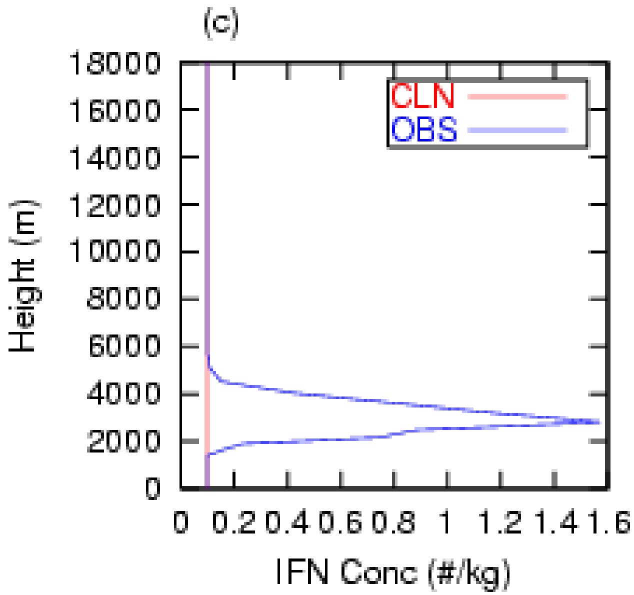
Simulations of Florida Thunderstorms during a Saharan Dust Event over South Florida



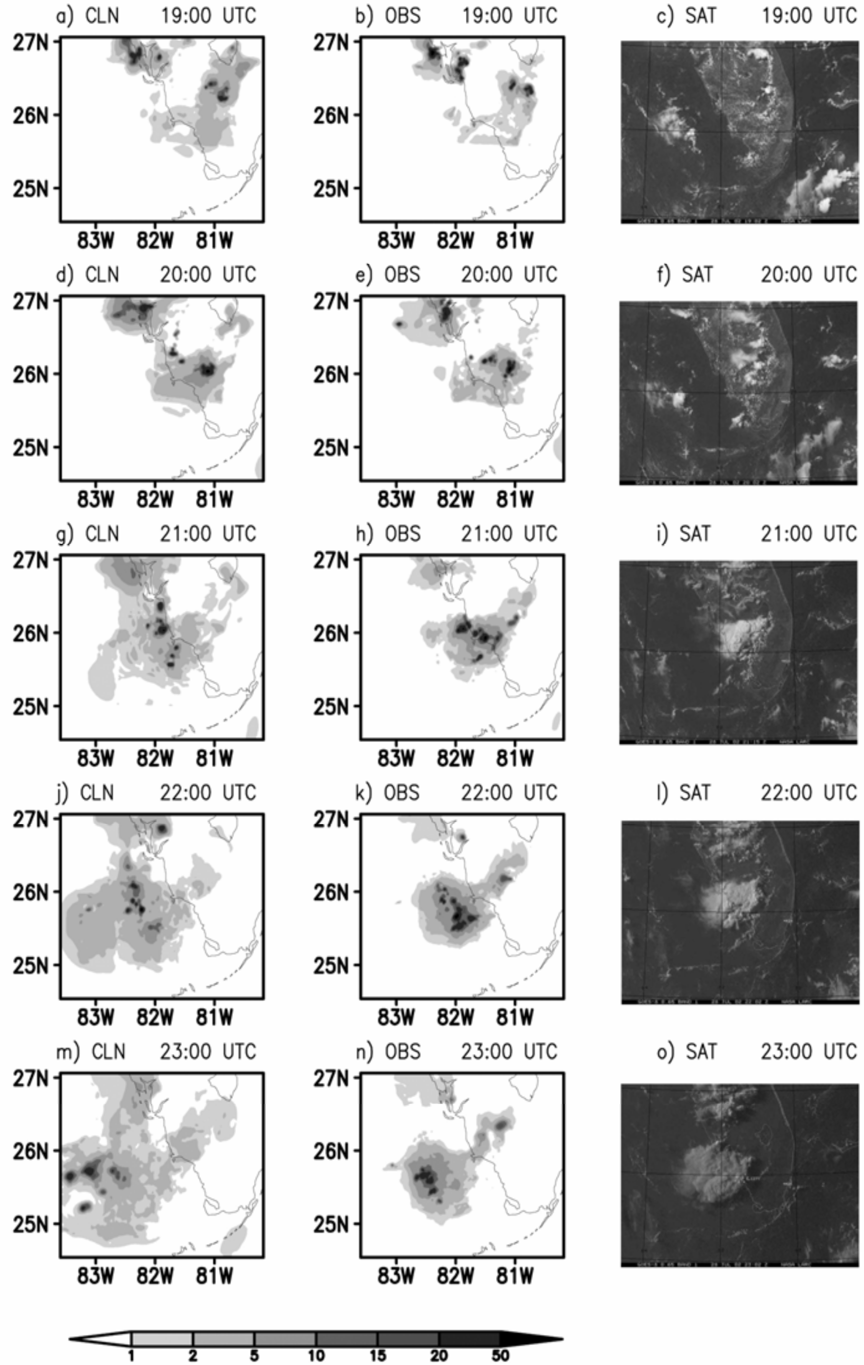
Based on van den Heever et al., 2006

- 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



a) CLN 19:00 UTC
b) OBS 19:00 UTC
c) SAT 19:00 UTC
d) CLN 20:00 UTC
e) OBS 20:00 UTC
f) SAT 20:00 UTC
g) CLN 21:00 UTC
h) OBS 21:00 UTC
i) SAT 21:00 UTC
j) CLN 22:00 UTC
k) OBS 22:00 UTC
l) SAT 22:00 UTC
m) CLN 23:00 UTC
n) OBS 23:00 UTC
o) SAT 23:00 UTC
27N
26N
25N
83W
82W
81W
1
2
5
10
15
20
50

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

Summary of findings:

- Updrafts are consistently stronger and more numerous in the dust case, early on in the convective cycle
    - driven by the latent heat release due to freezing of larger amounts of supercooled water associated with higher aerosol concentrations within the storm.
- 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

- Overall precipitation volume is greatest for the IN case, least for dust acting as CCN/GCCN/IN, and middle of the pack for dust acting as CCN-only and the clean case, early during the convective period
- Precipitation volume is greatest for the clean case, least for dust acting as CCN only, and middle of the pack for dust serving as CCN/GCCN/IN near sundown

Reasons for such complex behavior:

- Dust is depleted by early convection so that later in the day convection is operating mainly on clean aerosol
- Cold pools generated by early convection triggers new convection whose behavior depends on interactions with other storms and their cold pools and with seabreeze convergence zones

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

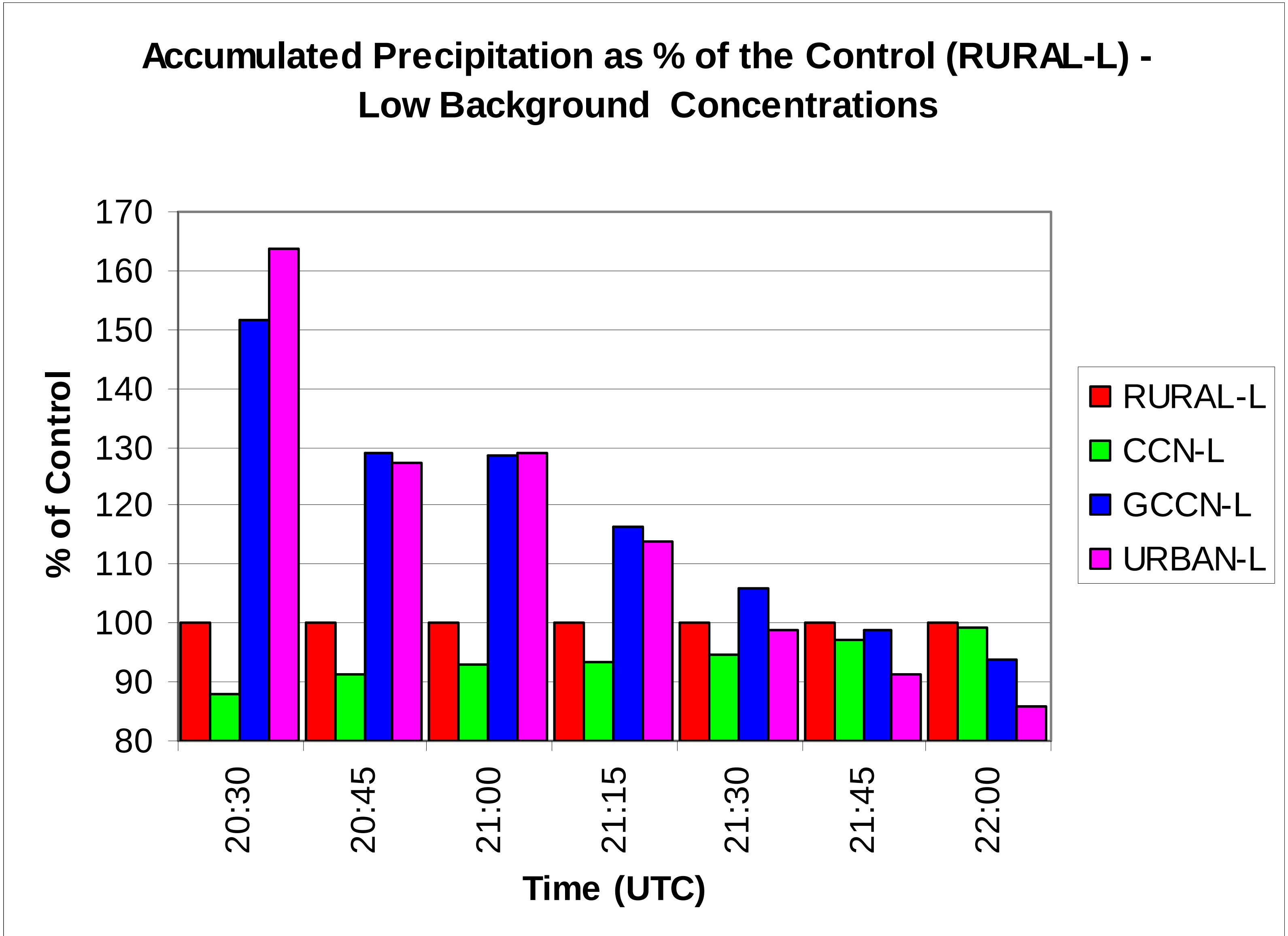
- High background:

Rural: CCN: 1200 cc^{-1}; GCCN: 0.1 cc^{-1}
Urban: CCN: 2000 cc^{-1}; GCCN: 0.2 cc^{-1}

- Low background:

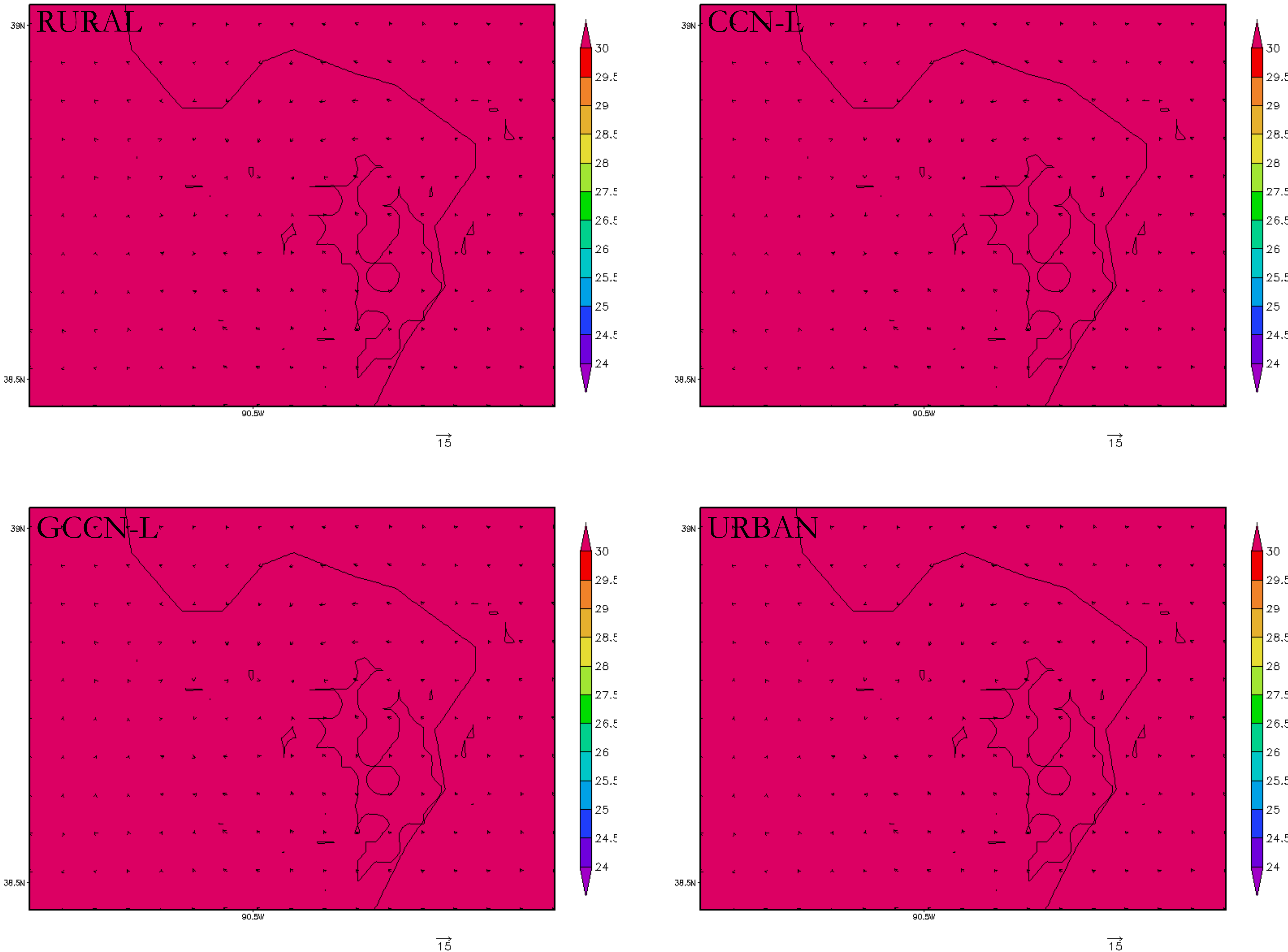
Rural: CCN: 800 cc^{-1}; GCCN: 0.01 cc^{-1}
Urban: CCN: 2000 cc^{-1}; GCCN: 0.2 cc^{-1}

Downwind Precipitation
Low Background Concentrations



Accumulated 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


RURAL
CCN-L
GCCN-L
URBAN
39N
38.5N
90.5W
15
30
29.5
29
28.5
28
27.5
26.5
26
25.5
25
24.5
24

Summary of urban 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.**

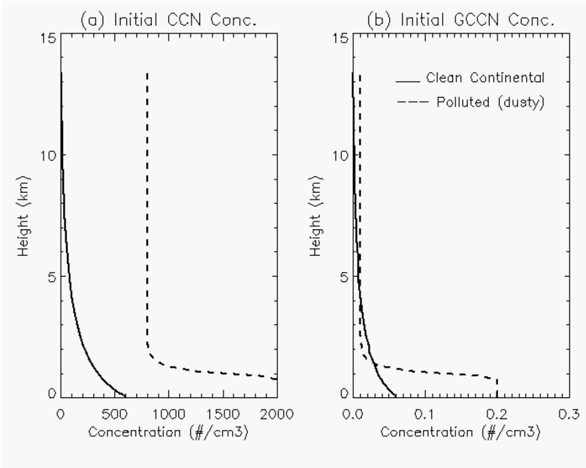
Possible Aerosol Influence on Tornado Genesis

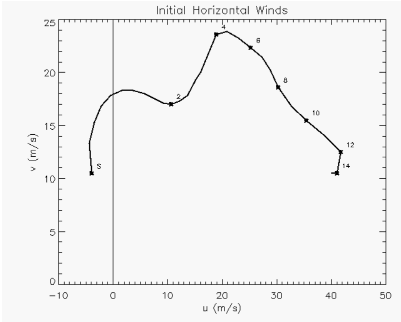
- There is observational evidence that the air within RFDs of tornadic supercell storms is more buoyant and potentially buoyant(higher CAPE) than in non-tornadic supercell storms
- Markowski et al.,(2002) also found that there was a high correlation between the coldness of the downdraft and the ambient(inflow) relative humidity. More buoyant low-level downdrafts were found in moist level environments than dry. This is also consistent with low LCLs in TC tornado environments as noted earlier.

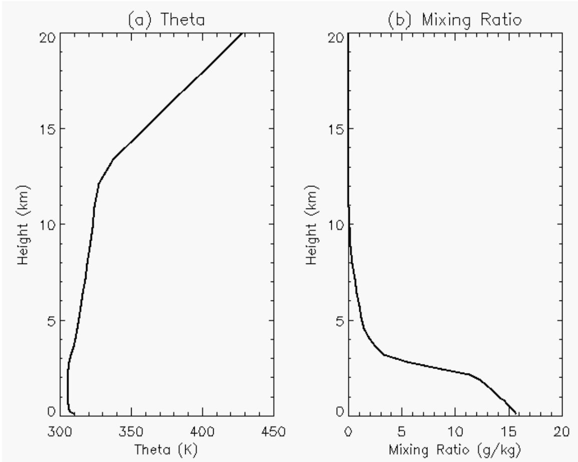
- Besides the relative humidity at downdraft source levels and the magnitude of precipitation rates, van den Heever and Cotton(2004) and Gilmore et al.,(2004) have shown that when hailstones and raindrops are relatively large, the evaporation rates and melting rates in downdrafts is less. This is a result of the fact that for a given hydrometeor water content, owing to the larger surface to volume ratio for small hailstones/raindrops relative to larger hydrometeors, and that both melting and evaporation occur primarily on the surface of a raindrop(hailstone), greater cooling will occur in downdrafts composed of small raindrops and hailstones than larger particles.

Methods

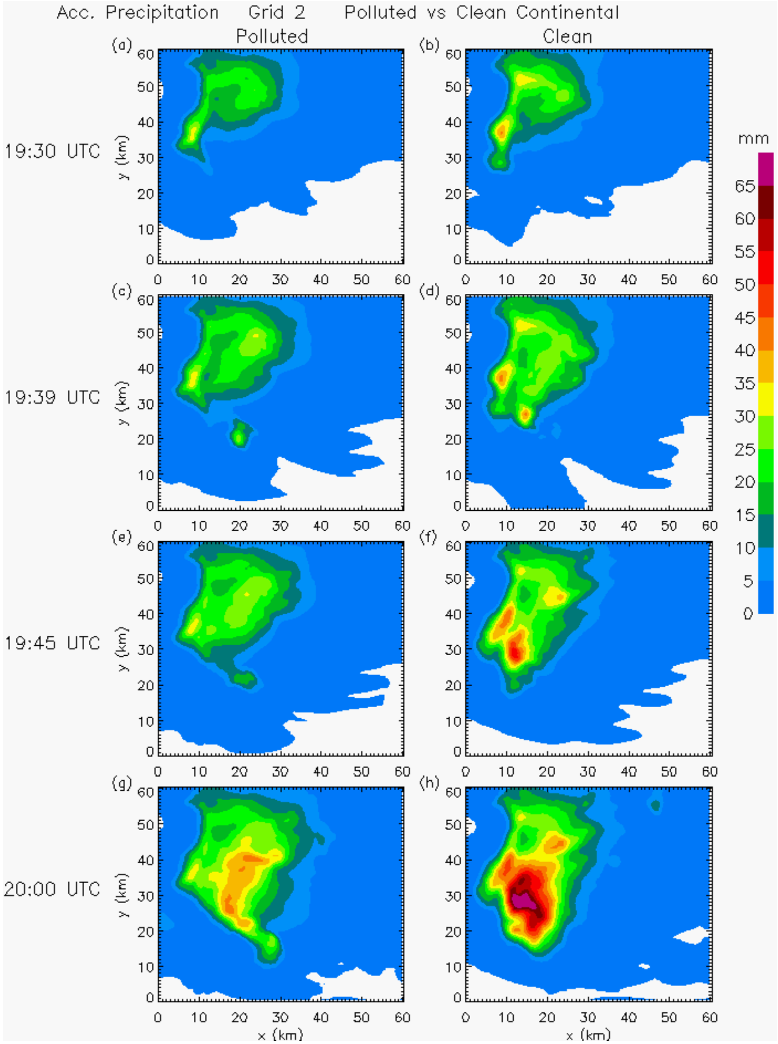
- Model setup: RAMS version 4.3.0
  - Cotton et al. (2003)
  - 2-moment microphysics
  - No radiation, surface friction, terrain
  - Convection explicitly resolved on all grids
  - 2 hour simulation
- Nested grids in Cartesian coordinates
  - Grid 1: 149x149 km, 1 km spacing
  - Grid 2: 60.33x60.33 km, 333 m
    - Initialized at 60 min
  - Grid 3: 38.44x21.78 km, 111 m
    - Initialized at 85 min
- 2 simulations with different initial profiles of CCN and GCCN concentrations
  - Clean continental (control; CLN)
  - Polluted (dust-laden; POL)
- Initialized with a homogeneous supercell-producing environment
  - Arbitrary start time of 1800 UTC

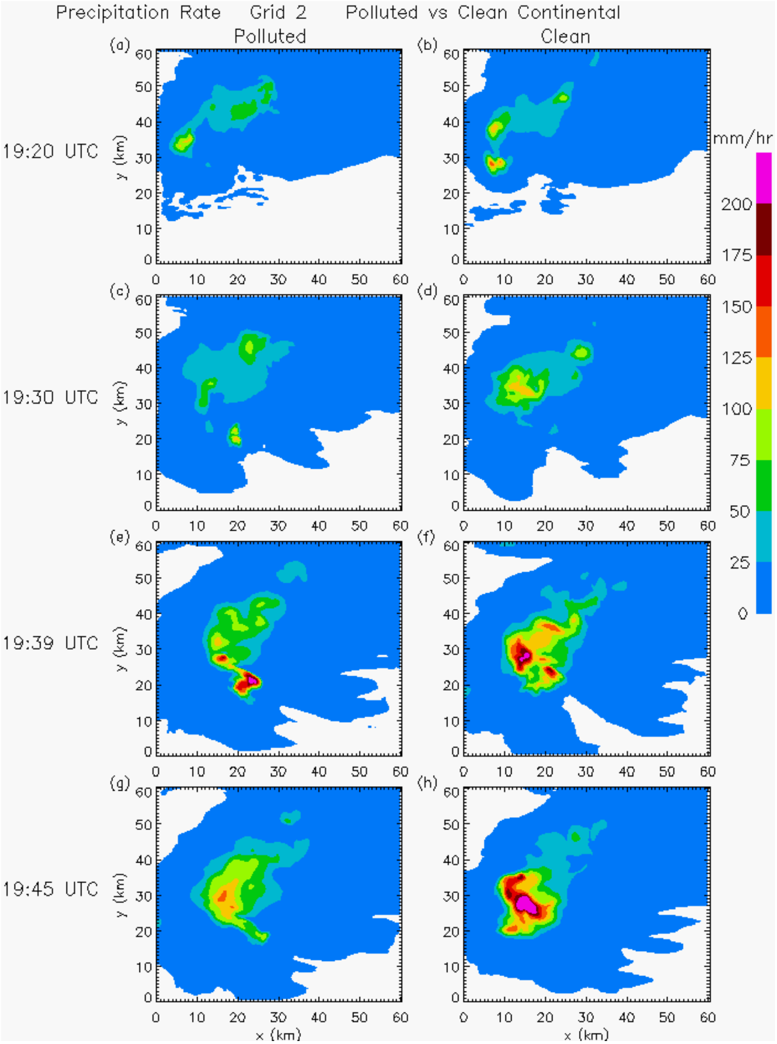






Precipitation

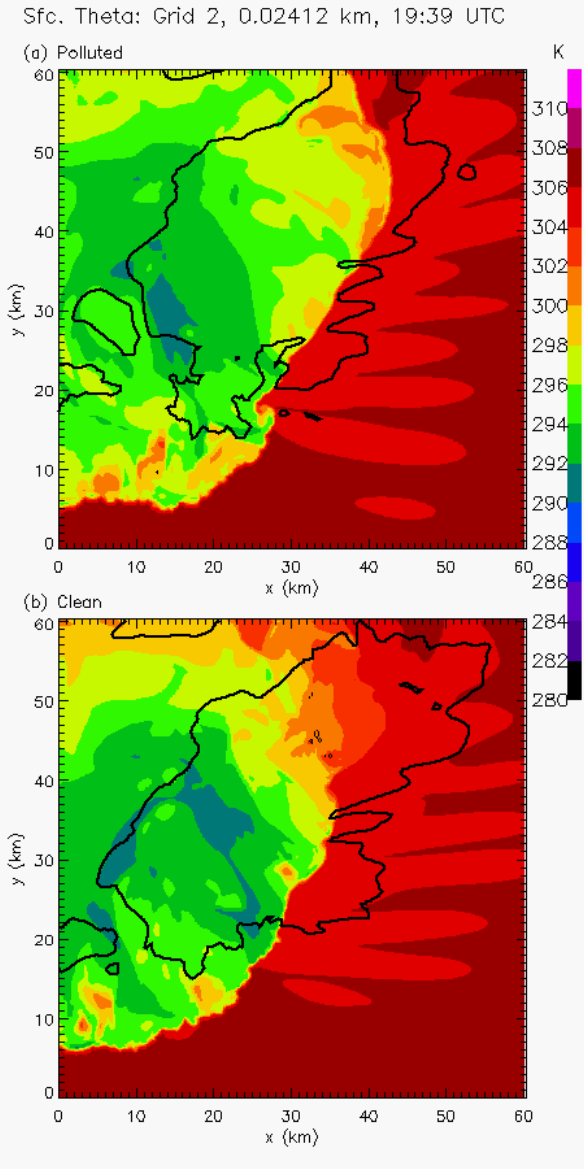




- Enhanced precipitation processes in CLN case
  - Enhanced FFD in CLN case

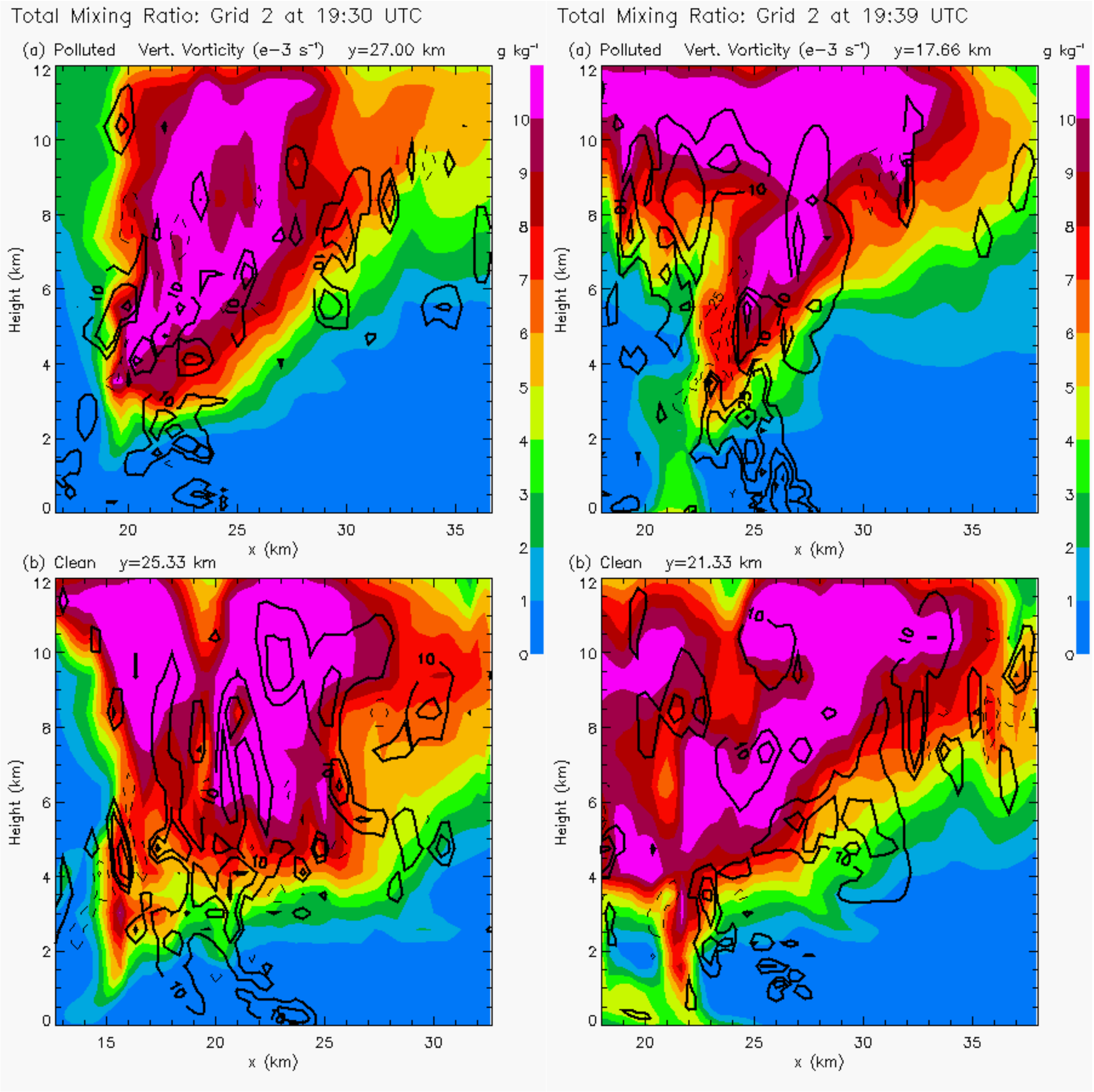
Surface Cold Pool

- Minimum temperatures similar between cases
- 2 K warmer near vortex / gust front in POL case
- FFD creates stronger cold pool at storm's leading edge in CLN case



Vertical Cross sections

- Vertical vorticity more vertically-stacked in POL case
  - Formation of tornado-like vortex
  - No vortex coupling in CLN case
  - Gust front effect?



Discussion

- Enhanced aerosol concentrations in the polluted (dust-laden) simulation weakened/slowed precipitation processes within both the RFD and FFD
  - A relatively weak cold pool was produced at the updraft-downdraft interface, allowing for a more favorable environment for tornadogenesis, where the low-level mesocyclone remained vertically stacked
  - Both the RFD and FFD in the clean simulation contained higher amounts of precipitation, more evaporative cooling, and thus a stronger surface cold pool that caused the RFD to dissipate rapidly compared to the polluted case. This resulted in a singular gust front that advected away more rapidly from the storm system, separating the low-level mesocyclone from its near-surface updraft and vorticity source and thus hindering the tornadogenesis process.
- This study did not find any significant differences in updraft intensity between simulations and therefore did not find any hail size dependence on updraft strength between the simulations

Aerosol Influence on Tropical Cyclones

Introduction

- This is a summary of results of simulations of the impact of African dust on hurricane intensity (Zhang et al., 2007; Zhang, 2008)

RAMS Setup

- RAMS was initialized with the pressure, temperature and wind fields of an axisymmetric MCV consistent with observations obtained from several pre-TC MCVs (Montgomery et al., 2006).
- Three nested domains with horizontal resolutions of 24, 6 and 2 km were used.
- RAMS was initialized with a horizontally uniform Jordan sounding (Jordan, 1958)

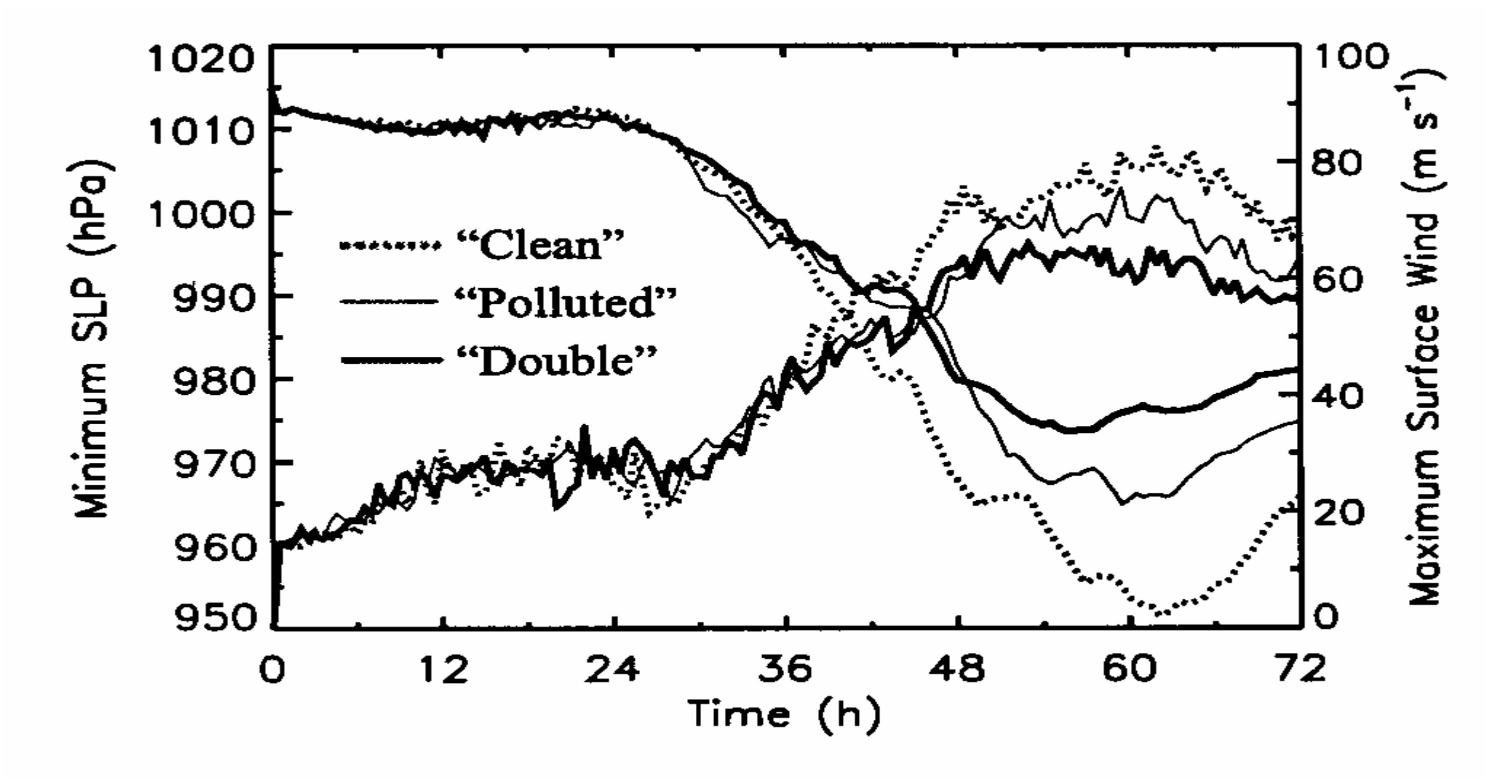
- The MCV was allowed to grow for 3 days in a zero wind environment over the ocean with a constant sea surface temperature (SST) of 29C
- The two-moment bin-emulating microphysics scheme described in Cotton et al. (2003) and Saleeby and Cotton (2004), in which bin microphysics for collection and sedimentation was used.
- The scheme includes two modes of droplets and explicit activation of CCN and GCCN(Saleeby and Cotton *(*2004)

- CCN is horizontally homogeneous. "Clean" has 100cm^{-3} from surface to 25km.
- "Polluted" enhanced the CCN in 1km-5km to 1000cm^{-3}.
- "Double" has CCN of 2000cm^{-3} in 1-5km.
- Intermediate values of 500/cc and 1500/cc were also run by Zhang(2008) and even 101/cc

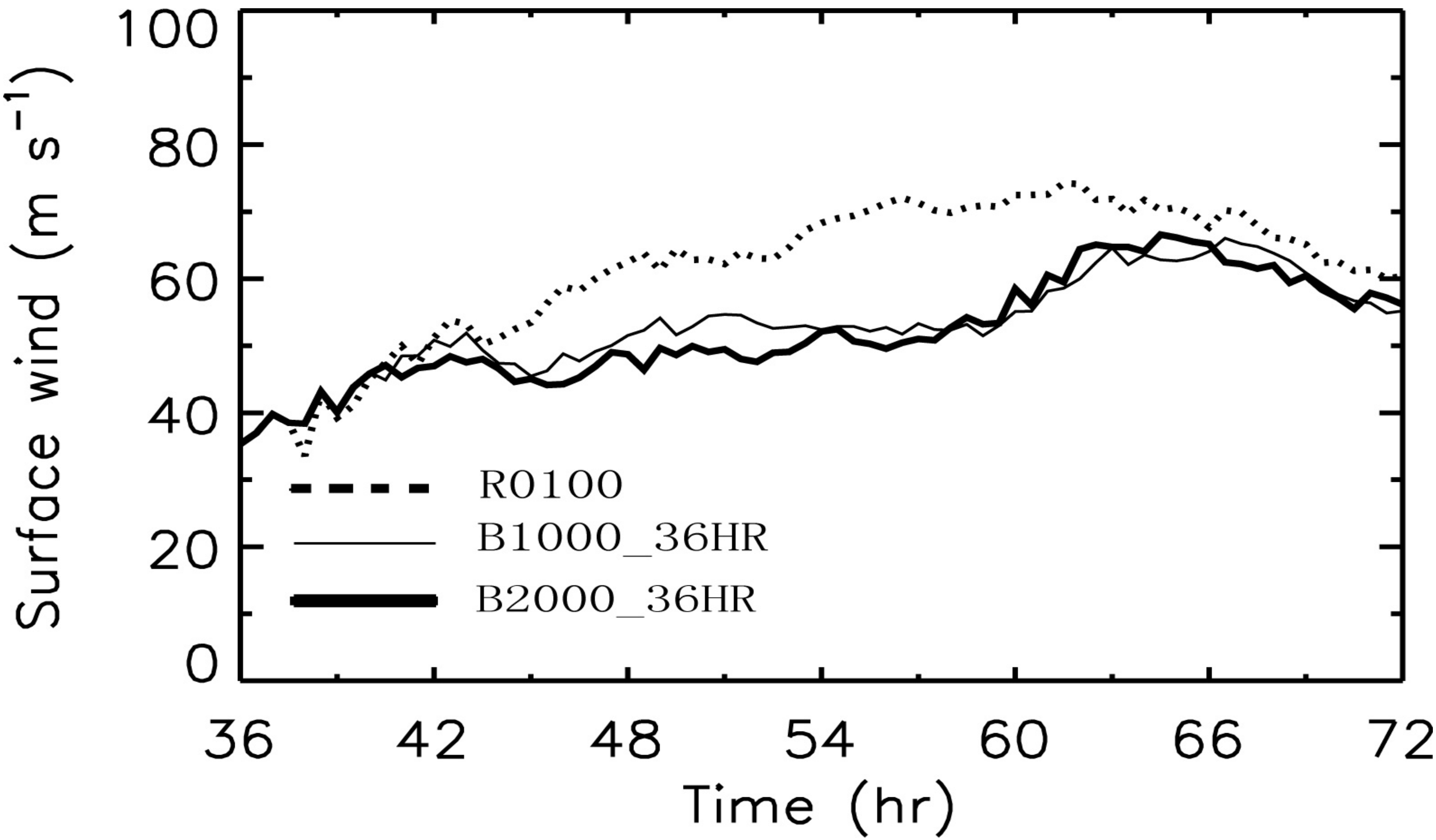
- Zhang(2008) also performed simulations with CCN introduced after 36h of simulation at the boundaries of Grid#3 or just in Grids#1 and 2.
- Similarly CCN was introduced at the boundaries at 60h.

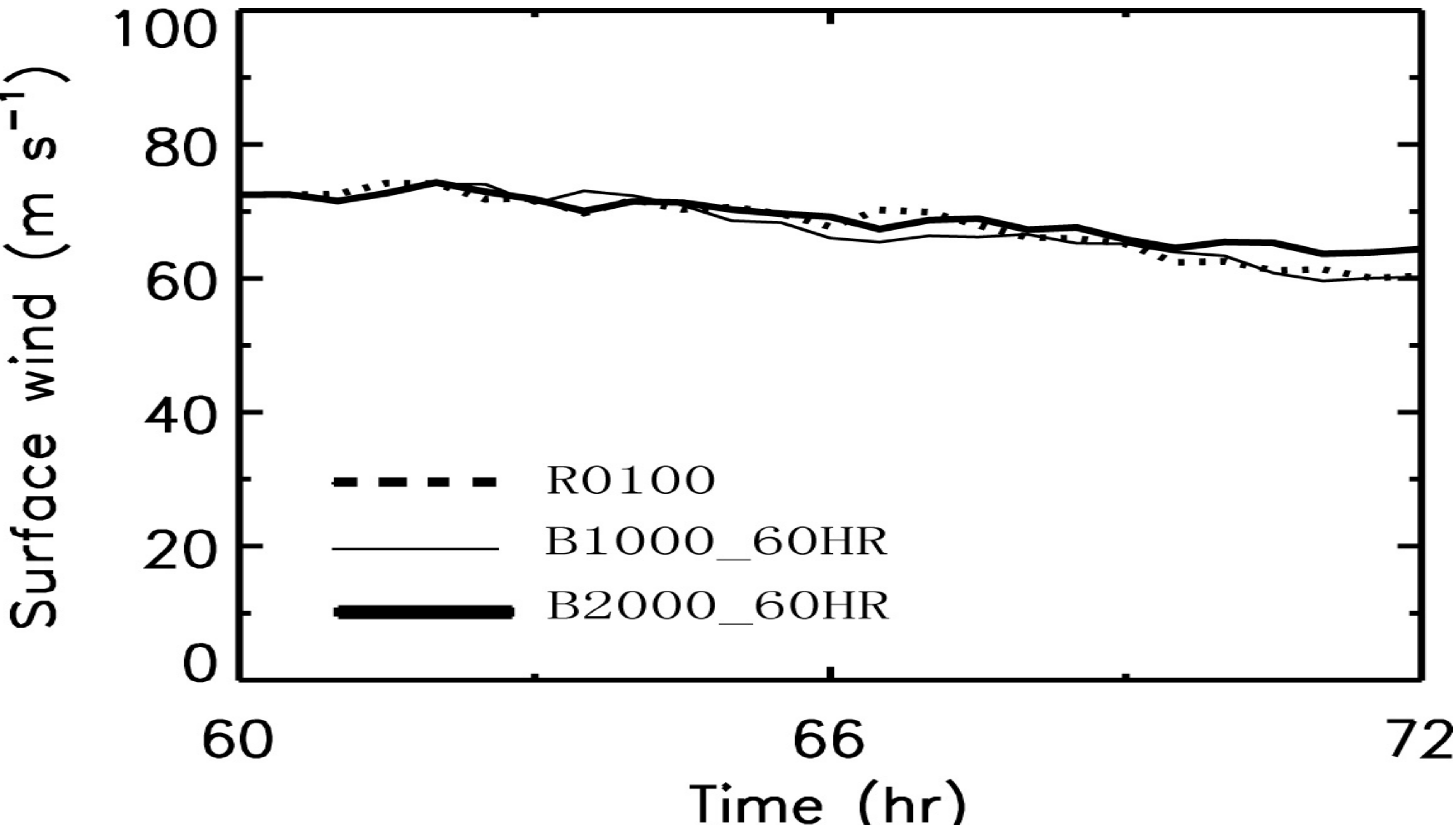
Results

“Clean” (dotted line), “Polluted” (thin solid line) and “Double” (thick solid line).



Simulations with CCN at boundaries at 36h

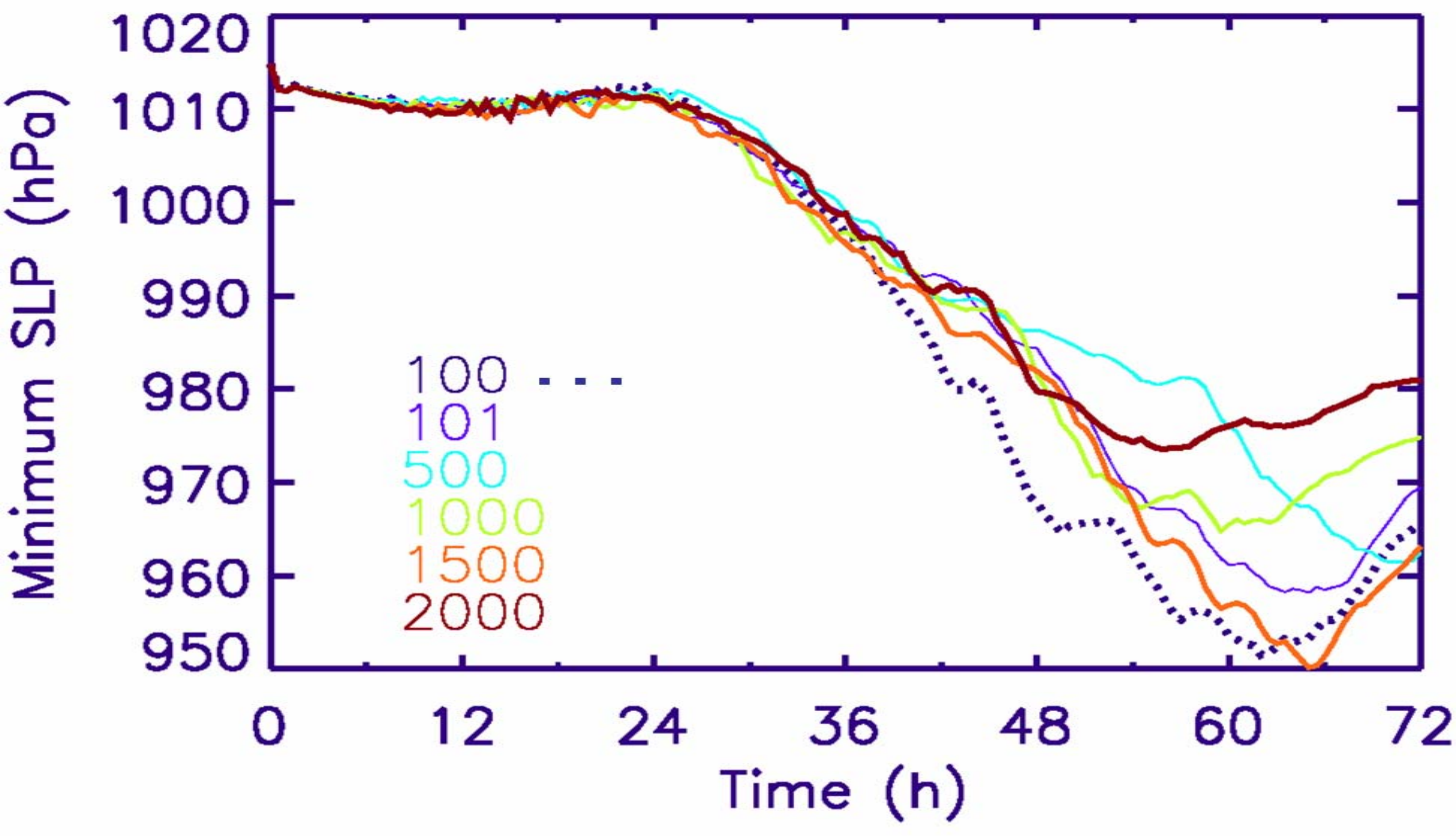




100
80
60
40
20
0
Surface wind (m s-1)
60
66
72
Time (hr)
R0100
B1000_60HR
B2000_60HR

- Impact of introducing CCN at boundaries at 36h were lessoned but still significant
- By 60h the storm was more mature and dynamically “stiff” and responded little to CCN

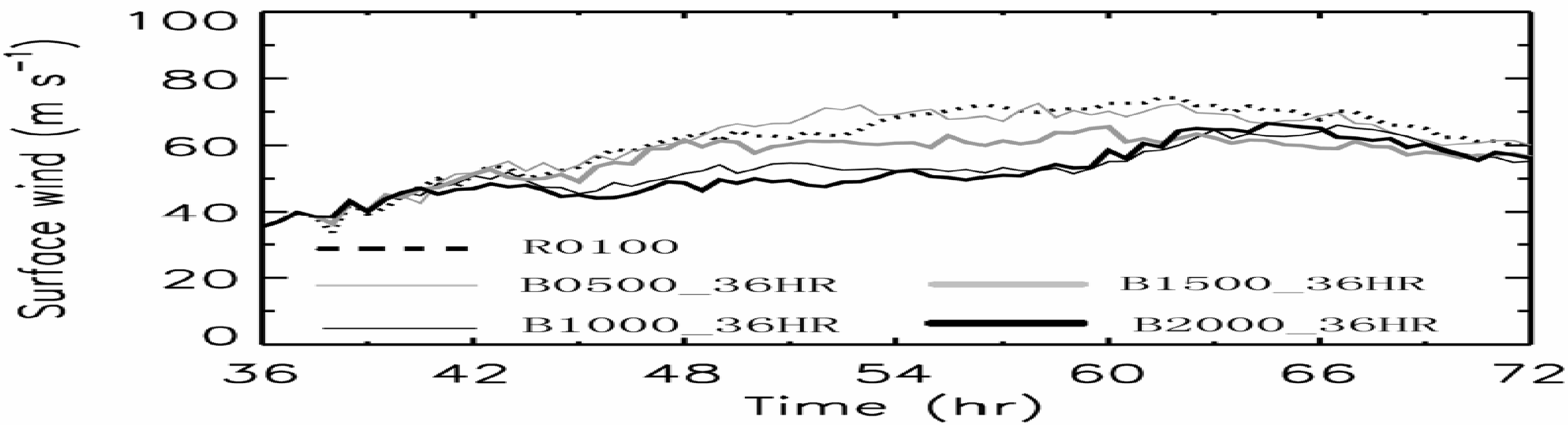
What about the intermediate values of CCN introduced initially?

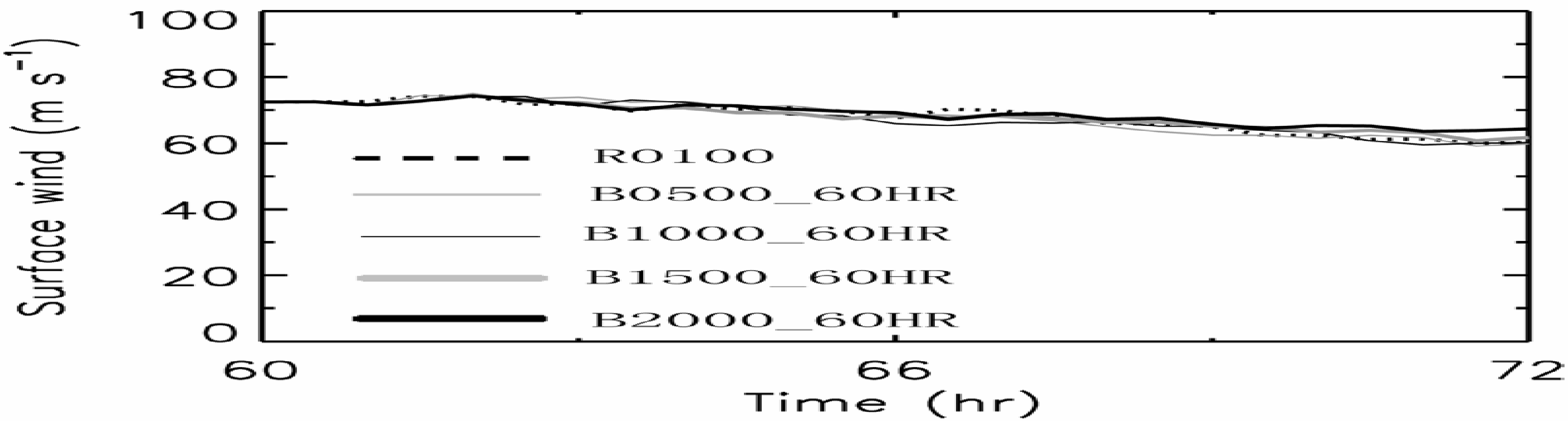


Oh-Oh!

- Results are no longer monotonic with increasing CCN!!

Nor at 36h and 60h!!





- Note that the time at which the greatest response to CCN occurs corresponds to the time in which spiral rainbands form in the simulation.
- Zhang (2008) concluded that the spiral rainbands divert enthalpy from the eyewall region thus contributing to a weakening of the storm.

- Note that the simulations do not reveal any significant response to enhanced CCN in the eyewall region or within a radius of 45km.
- This is because the enhanced CCN are washed out well before they are transported close to the eyewall. Throughout the simulations CCN concentrations in the eyewall region remain low and probably unrealistically low (about 1/cc or less) owing to the fact that sea-spray generation of CCN is not simulated.

Conclusions

- 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, time of introduction of aerosol, and scales of convection.