Effects of Aerosols on Microphysics and on Warm-Season Precipitation

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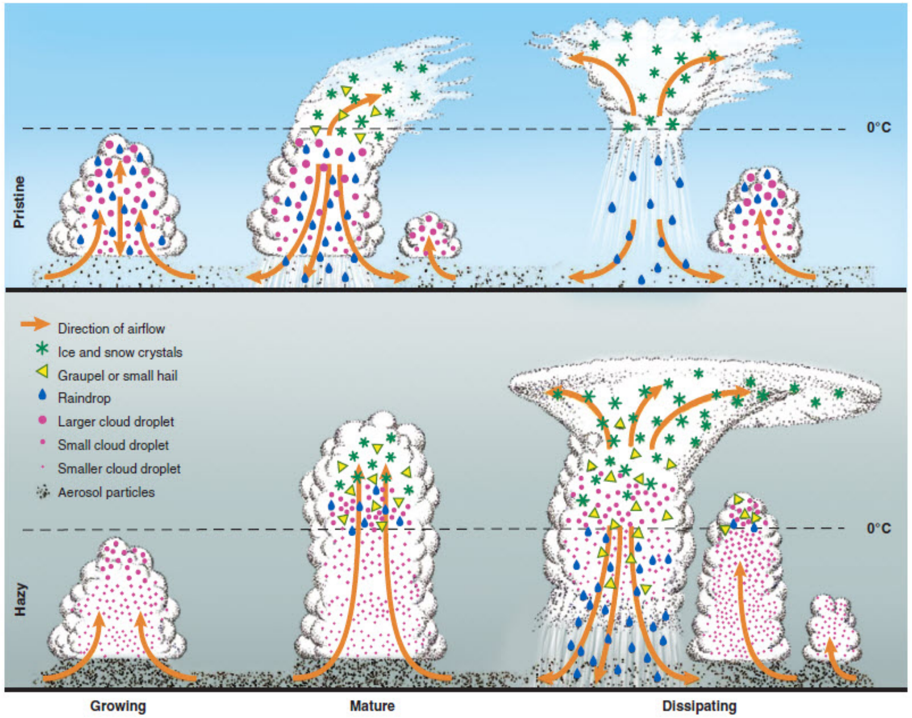
This study was supported and monitored National Oceanic and Atmospheric Administration (NOAA) under CREST Grant # NA11SEC4810004. The statements contained within the manuscript/research article are not the opinions of the funding agency or the U.S. government, but reflect the author's opinions.

23 July 2013

Convection, Microphysics, & Aerosols



Aerosols impact clouds and rainfall, including extreme rainfall events (Diem and Brown 2003; Molders and Olson 2004; Rosenfeld et al. 2008; Li et al. 2011), i.e.,

- Act as CCN/GCCN, they scatter and absorb solar radiation (a direct effect)
- Their radiative effects produce global warming/cooling (an indirect effect)
- They alter precipitation patterns and amounts, via modification of cloud micro-physics processes (Feingold et al. 1999)
- Impacting precipitation rate with changes in con-centration (Jiang et al. 2010)

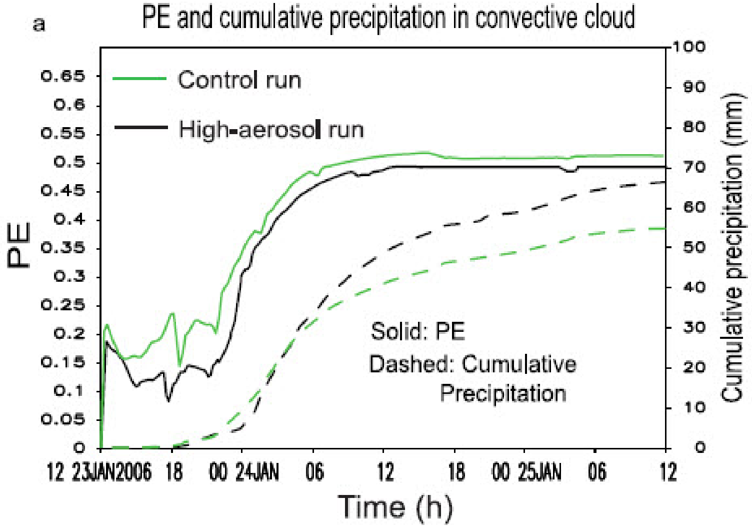
- Convection induced by urban environments transports aerosols deep into the atmosphere; even deeper with UHIs. Warm-cloud precip forms by a slow growth by condensation phase, followed by a rapid growth by C&C (see fig. below)

- If freezing-nuclei (aerosols) are lifted above the freezing level, ice crystals can form and grow by sublimation. These grow faster than surrounding super cooled liq droplets, and thus fall faster to trigger C&C (i.e., Bergeron process), which accelerates cold-cloud precip.

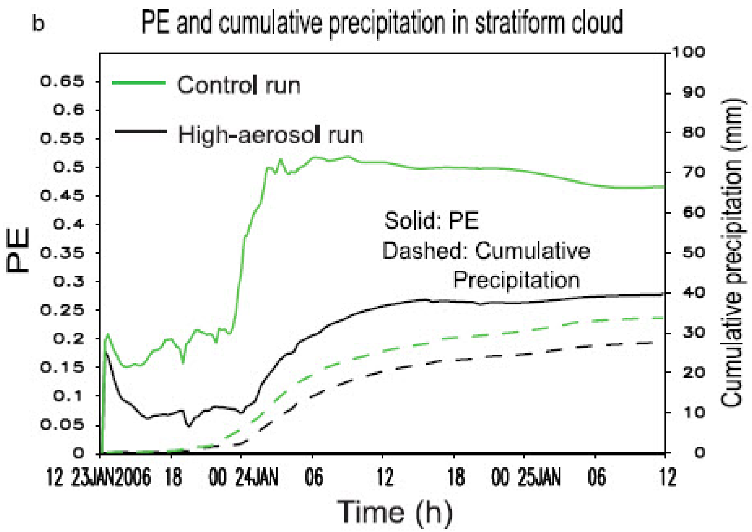
Urban aerosols typically range in size from 0.1 microns (CCN) to 100 microns (GCCN).

Aerosol Concentration Effects on Precipitation

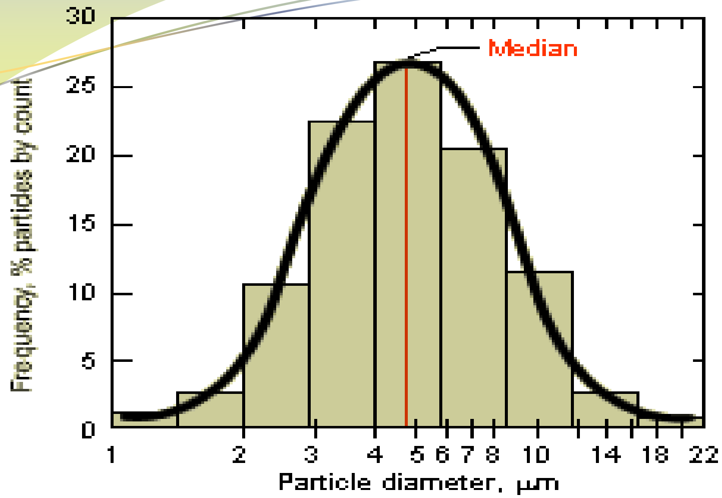
- **Precipitation efficiency (PE) and cumulative precipitation for a (a) convective and (b) stratiform cloud in the Tropical Western Pacific (Lee and Feingold 2010).**



- **Results show:**
  - **PE is much larger for stratiform-cloud in lower-concentration aerosol (i.e., control) run, while it is only slightly larger in the Cu-cloud run**
  - **Cumulative-precip increases with increased concentration in the convective cloud, and decreases with increased concentration in the stratiform cloud**

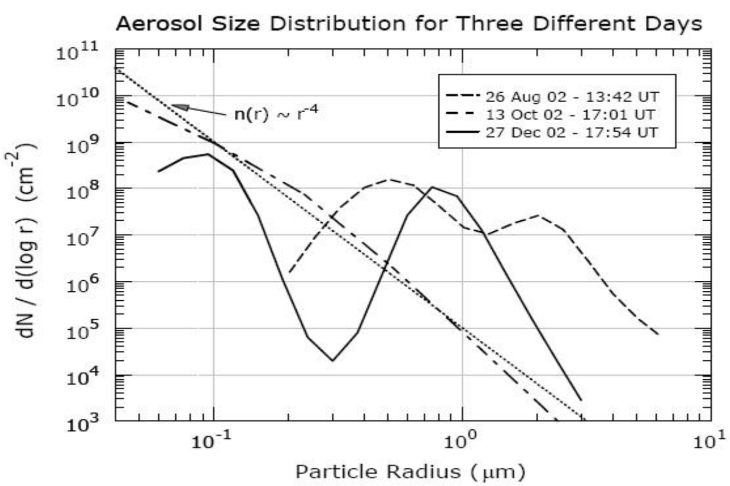


Model Input: Theoretical-PSD vs. Observed PSD



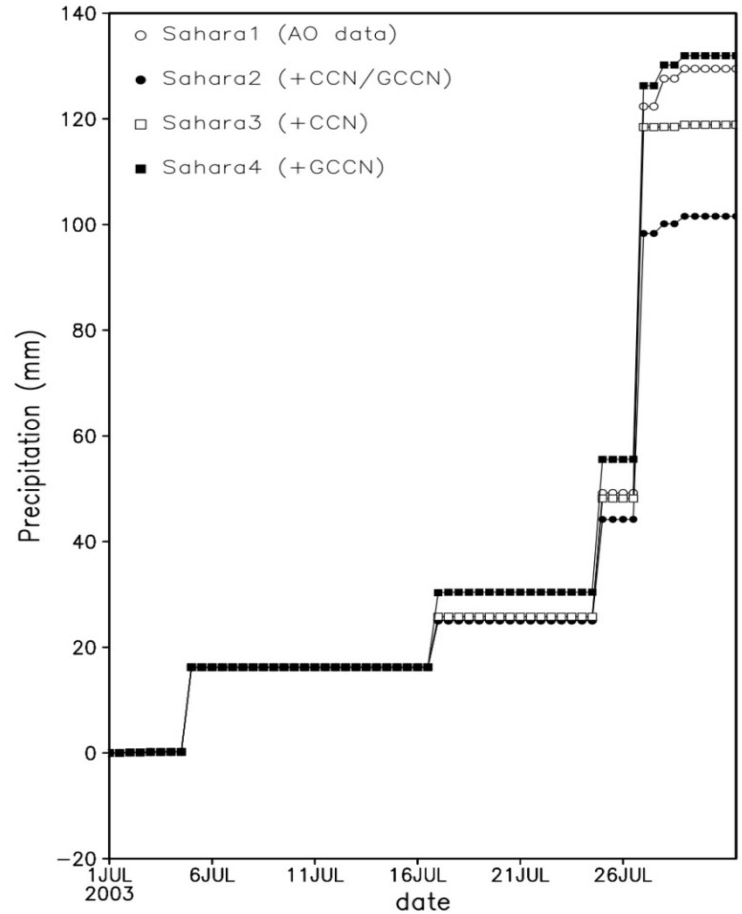
I mode

Modelers often assume a particle size distribution (PSD), as above, but actual PSDs may be obtained via ground obs (i.e., from the AERONET) or from satellites



2 modes- Splits CCN/GCCN

PSD data for the Arecibo Observatory (AO) on three days show different distributions, i.e., log-linear decrease vs. bimodal (Comarazamy et al. 2006)



Observed precip-totals at the AO (°), vs. RAMS modelled values (using bimodal-PSDs) show:

- large decreases with both extra CCN and GCCN (•), due to droplet-competition
- smaller decreases with only CCN (□)
- increases with only GCCN(■), due the C&C efficiency of GCCN (Comarazamy et al. 2006)

Fundamental Research Questions

Previous studies have shown that increased aerosol concentrations can either increase or decrease urban precip-amounts. The present research proposes to determine the effects of aerosol PSD variation on precip in an urban environment.

Overall question: How do aerosols effect precipitation in urban environments?

Sub-question 1: Can urban precipitation forecasts be improved with PSD ingestion?

Sub-question 2: How does aerosol-PSD affect total precipitation?

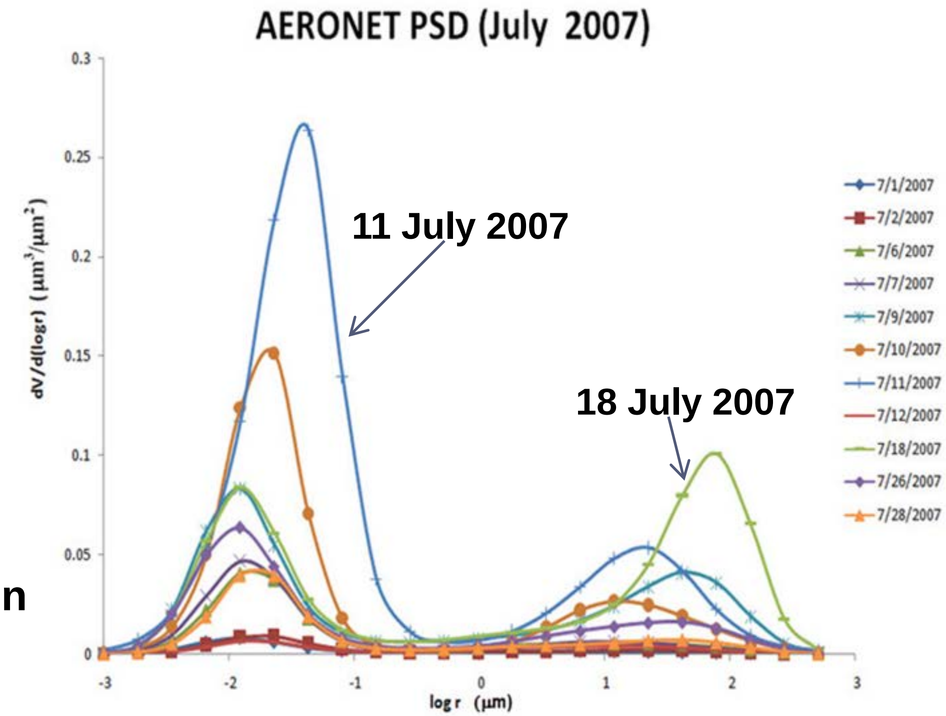
AERONET PSD-Data

- **AERONET algorithm determines percentage of spherical particles required to give best fit to measured spectral sky-radiance angular-distribution (Eck et al. 2012)**

- **PSD retrievals are QAed (version 2 and level 1.5) via Holben et al. (2006)**

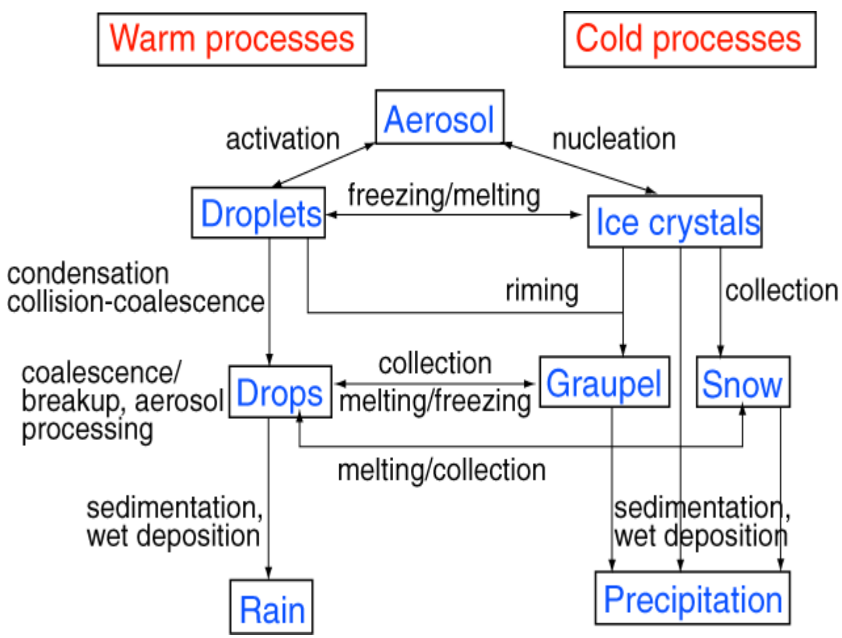
- **Comparisons of size distributions between in-situ and AERONET-retrievals for smoke in South America, Southern Africa, and North America showed volume median radii r mostly within ~0.01 μm (Reid et al. 2005)**

- **Of distributions (by volume) for July 2007 (on right), the 11th (blue) had the highest volume of fine mode CCN (r < 1 μm) & the 18th (green) had the highest volume (V) of coarse mode GCCN particles (r > 1 μm); these were selected for further investigation**



RAMS Meso-Met Model

Regional Atmospheric Modeling System (RAMS) uses a two-moment scheme (Saleeby and Cotton 2004, 2008), which predicts hydrometeor mass mixing ratio and number concentration (see Eqs.); it also allows ingestion of bimodal PSDs (see Fig). It extends the two-moment approach to cloud-droplet distribution via parameterization of cloud-droplet formation from activation of cloud condensation nuclei (CCN) and giant CCN (GCCN) within lifted parcels.



Navier-Stokes Equations:

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - \theta\frac{\partial \pi'}{\partial x} + fv + \frac{\partial}{\partial x}\left(K_m\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - \theta\frac{\partial \pi'}{\partial y} - fu + \frac{\partial}{\partial x}\left(K_m\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right)$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - \theta\frac{\partial \pi'}{\partial z} - \frac{g\theta_v'}{\theta_0} + \frac{\partial}{\partial x}\left(K_m\frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_m\frac{\partial w}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_m\frac{\partial w}{\partial z}\right)$$

Thermodynamic Equation:

$$\frac{\partial \theta_{il}}{\partial t} = -u\frac{\partial \theta_{il}}{\partial x} - v\frac{\partial \theta_{il}}{\partial y} - w\frac{\partial \theta_{il}}{\partial x} + \frac{\partial}{\partial x}\left(K_h\frac{\partial \theta_{il}}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h\frac{\partial \theta_{il}}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_h\frac{\partial \theta_{il}}{\partial z}\right) + \emptyset_\theta$$

Mass-Continuity Equation:

$$\frac{\partial \pi'}{\partial t} = -\frac{R\pi_0}{c_v\rho_0\theta_0}\left(\frac{\partial \rho_0\theta_0 u}{\partial x} + \frac{\partial \rho_0\theta_0 v}{\partial y} + \frac{\partial \rho_0\theta_0 w}{\partial z}\right)$$

Water-Species Mixing-Ratio Equations, n = 1, 8 for : 1 cloud droplets, 2 rain, 3 ice, 4 snow, 5 aggregates, 6 graupel, 7 hail, and 8 drizzle

$$\frac{\partial r_n}{\partial t} = -u\frac{\partial r_n}{\partial x} - v\frac{\partial r_n}{\partial y} - w\frac{\partial r_n}{\partial x} + \frac{\partial}{\partial x}\left(K_h\frac{\partial r_n}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h\frac{\partial r_n}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_h\frac{\partial r_n}{\partial z}\right) + \emptyset_r$$

CCNY-site AERONET PSD-data ingestion

To ingest observed PSD data into RAMS, daily V(r) distributions on selected July 2007 days were converted into daily r- & number N-distributions (diamonds). Blue & red (diamonds) are the mode r & N-values for the 11th & 18th, respectively; green lines show the average of July 2007 data for each of the r & N. Note that the larger GCCN r-values on the 18th does not translate into larger mode GCCN N-values; likewise for the CCN peak on the 11th.

Spherical Particles:

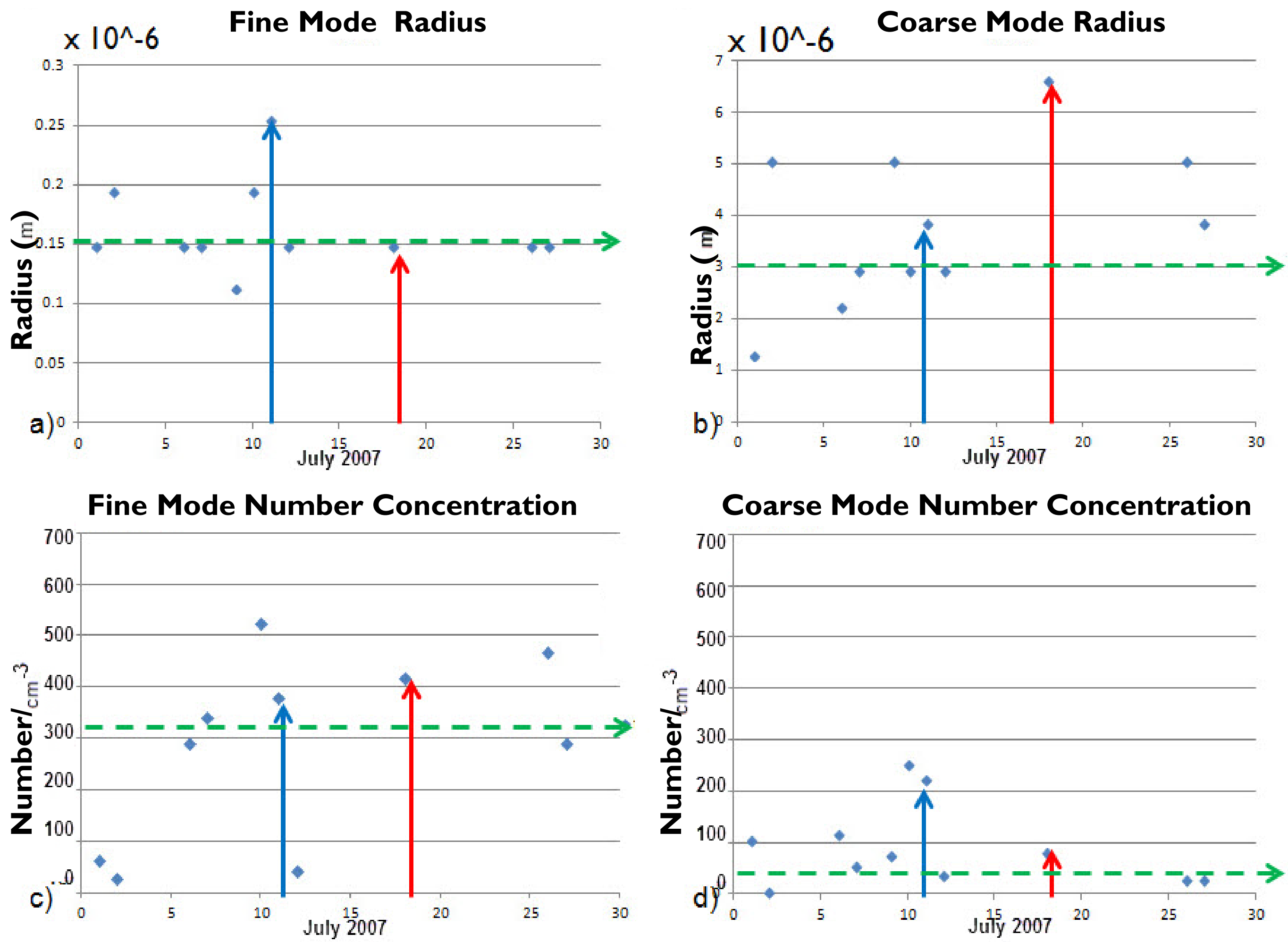
$$V(r) = \frac{4\pi}{3} * r^3$$

Number Distribution:

$$\frac{dN}{d(\log r)} = \frac{3}{4\pi r^3} * \frac{dV}{d(\log r)}$$

PSD ingestion-scenarios for RAMS simulations:

1) 11 July PSD for 11 July
2) 18 July PSD for 11 July
3) 11 July (no coarse) PSD for 11 July
4) 11 July (no fine) PSD for 11 July



Run 1 is "observed," while all other cases are "alternate."

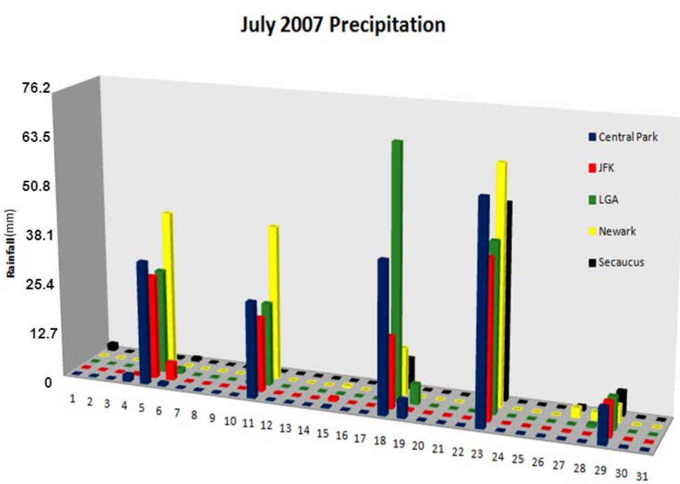
Case-Selection and Methodology

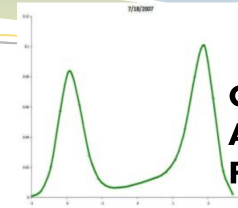
NYC was chosen because:

- **Most densely populated US city (Riley 2007)**
- **Hot & humid summers, with temps sometimes > 32°C**
- **PSD-data via AERONET**

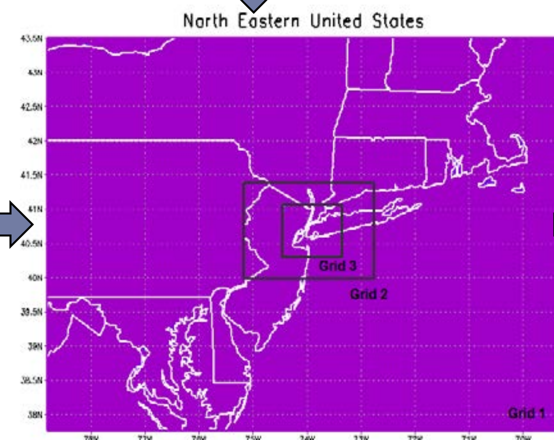
Time-period studied:

July 2007, with five warm-season rainfall events, with 11th and 18th selected for further investigation because of their high rainfall variability across region.



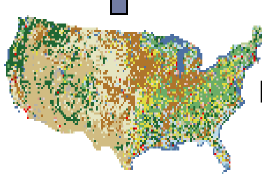


CCNY AERONET PSD



NCEP Reanalysis 2.5 x 2.5 deg

Results



NLCD Land Data 30 m Resolution

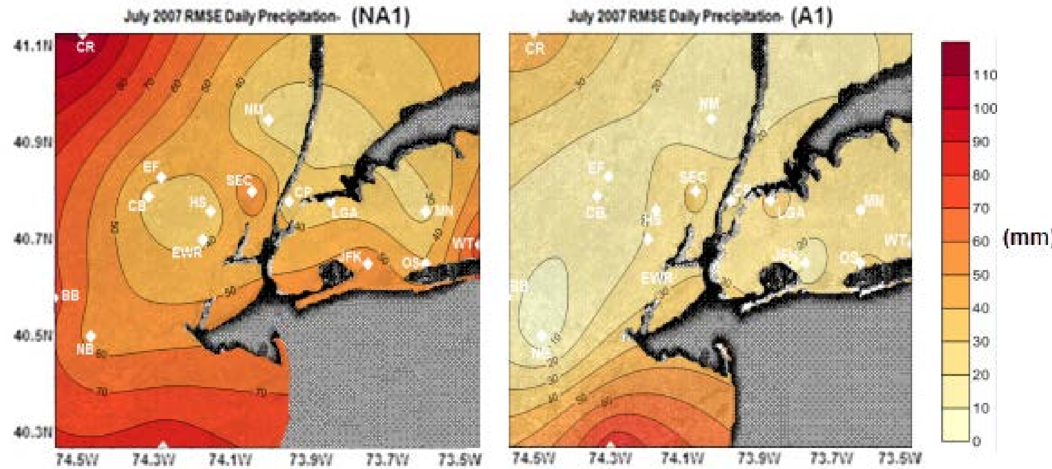
RAMS (2008) 16, 4, 1 km domains, Δt = 30 s

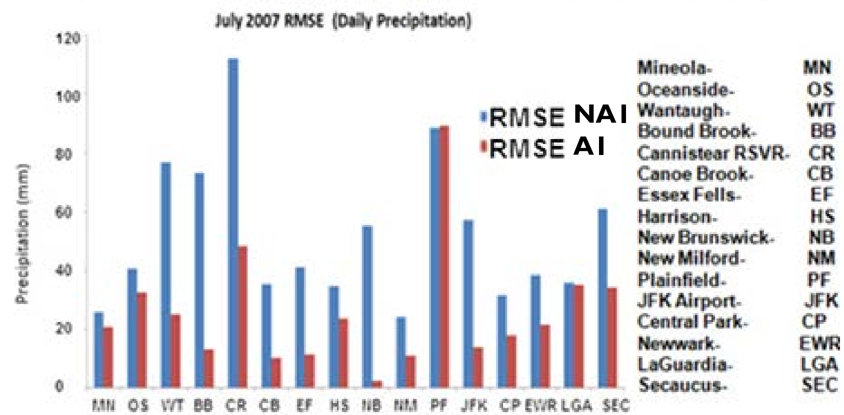
- **National Centers for Environmental Protection (NCEP) reanalysis met-data updated every 6 h, with a 2.5° x 2.5° resolution**
- **30 m resolution LCLU-data from National Land Cover Data (NLCD, 2006)**

Total Monthly Precipitation
(July 2007 simulations vs. NWS Obs- 2 simulations)

Site	NWS-Obs	NA1	A1	% Err NA1	% Err A1
MN	218	147	120	32.7	45.1
OS	110	125	115	13.4	4.3
WA	84	115	85	37.6	1.7
BB	120	180	120	49.5	0.3
CR	112	160	153	42.8	36.6
CB	223	193	150	13.4	32.7
EF	194	177	156	8.9	19.7
HS	163	155	164	5.1	0.4
NB	141	149	137	5.5	3.0
NM	183	120	125	34.6	31.8
PF	139	148	150	6.3	7.8
JFK	134	131	134	2.5	0.3
CP	175	150	177	14.3	1.1
EWR	170	179	171	5.0	0.3
LGA	180	168	180	6.7	0.04
SEC	81	98	83	21.7	3.1

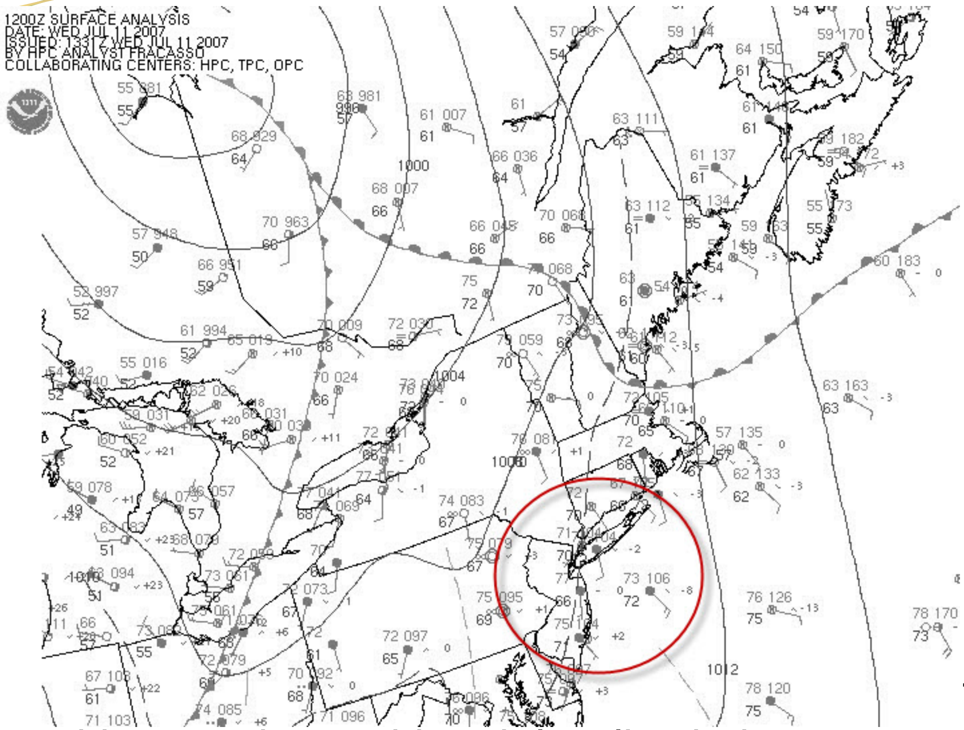
Bottom Line: Better results with ingestion in 12 of 16 cases (also see bar graph)



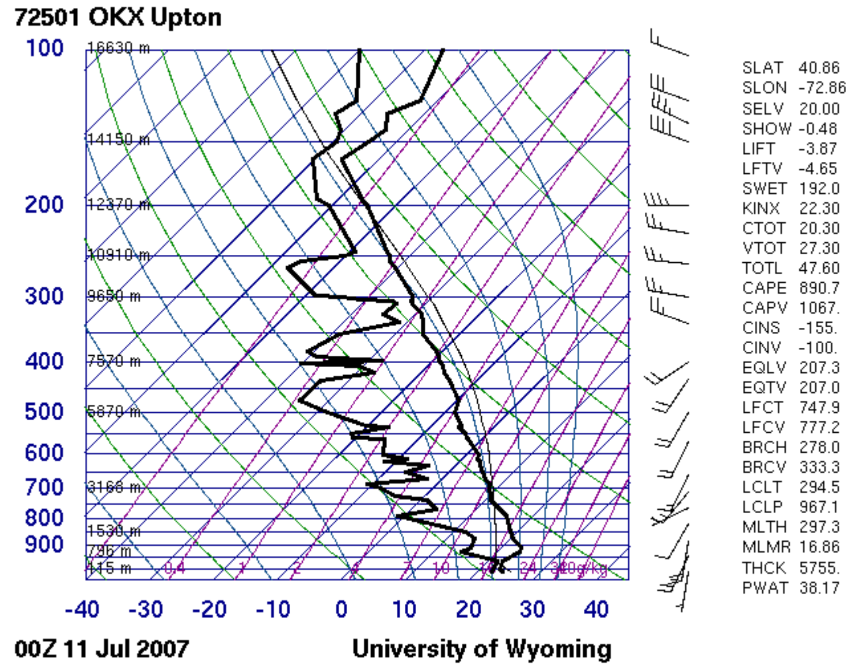


A month-long simulation (updated with obs daily regionally homogeneous PSDs) was compared to one without updates. Red values show better results.

11 July Surface-Pressure Skew-T Sounding ("Localized" case)



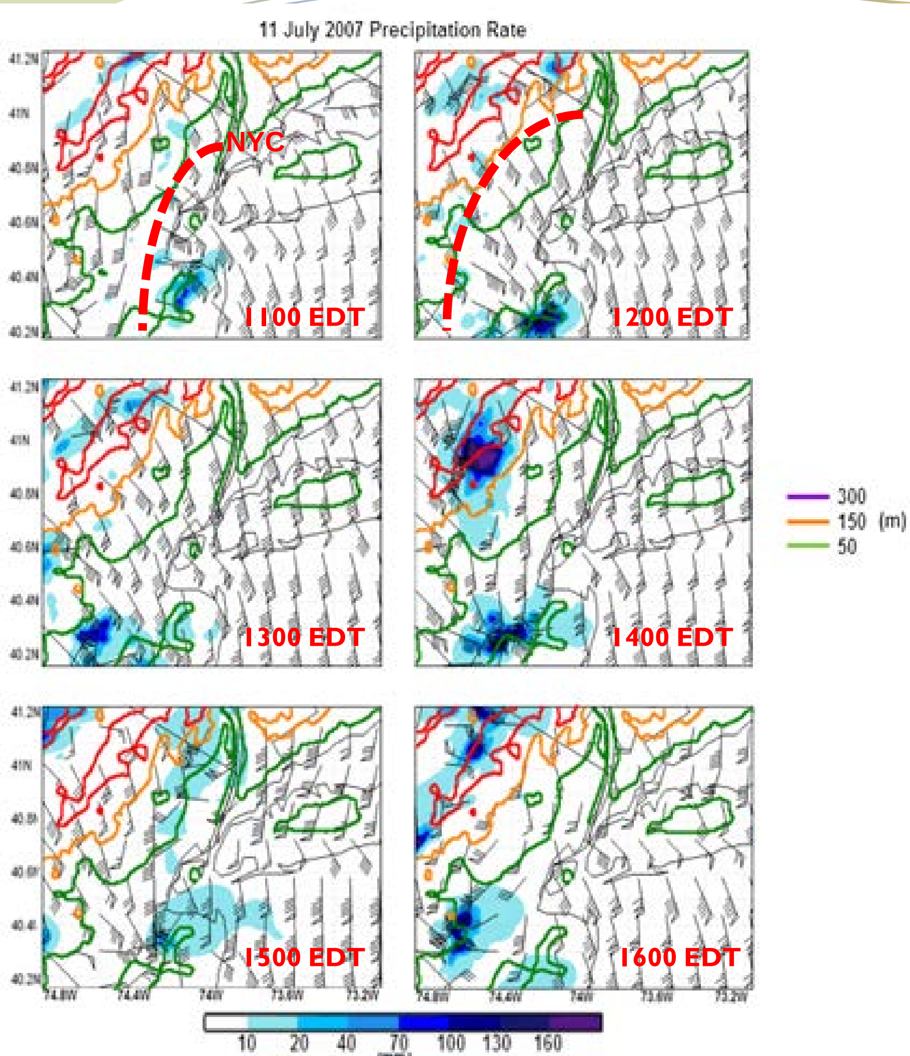
This event is considered "localized," because its rain was not due to a synoptic front. High pressure SE of NYC (not shown) and a N-S low-p trough through the city (dashed line) produce an observed southeasterly regional onshore-flow (sea breeze).

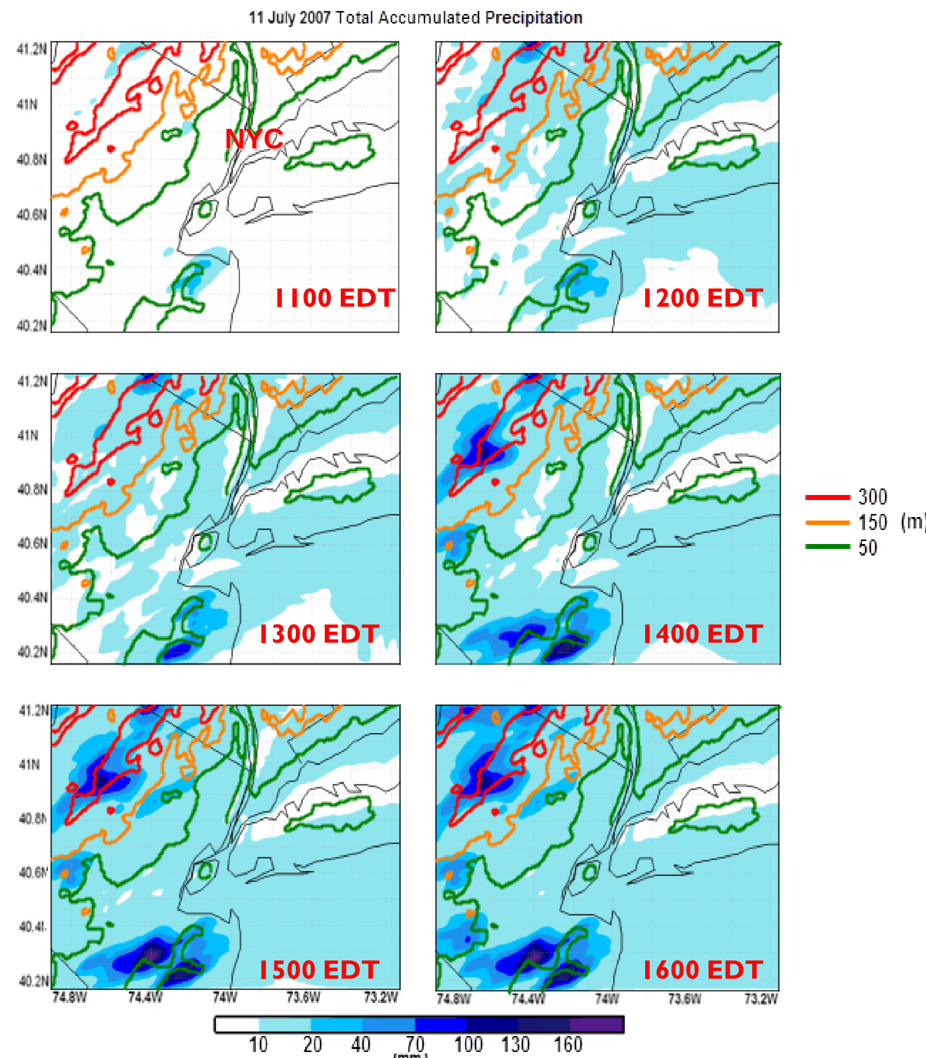


The CAPE value on at 00 UTC on 11 July (20 EDT on the 10th) was 890 J kg^{-1} in association with its relatively warm air. In the dry-layer up to 300 hPa (above a surface saturated layer), dew point temps are significantly lower than temp-values. CAPE values above 500 J kg^{-1} are associated with strong local convective influences.

Run 1 (uses obs fine-mode V-CCN max) 11 July 2007 (localized-case)

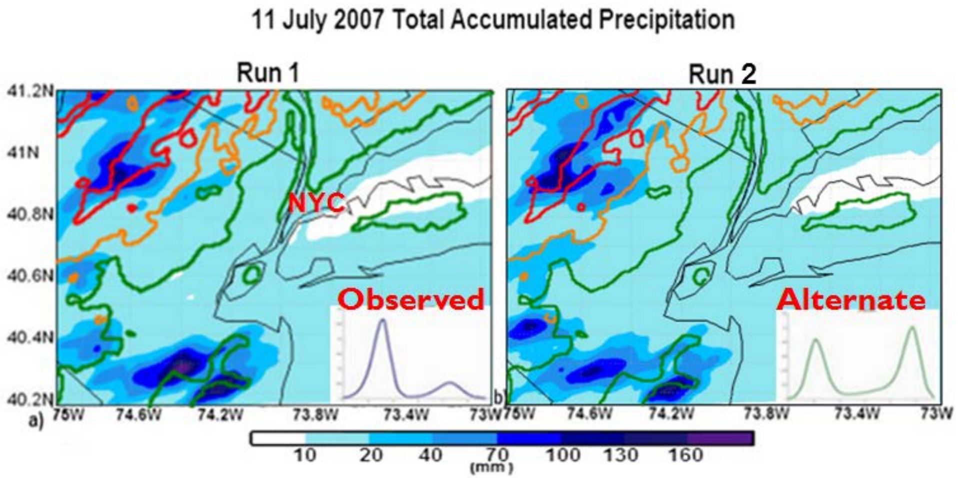
Precipitation Rate (mm/h) | Accumulated Totals (mm)

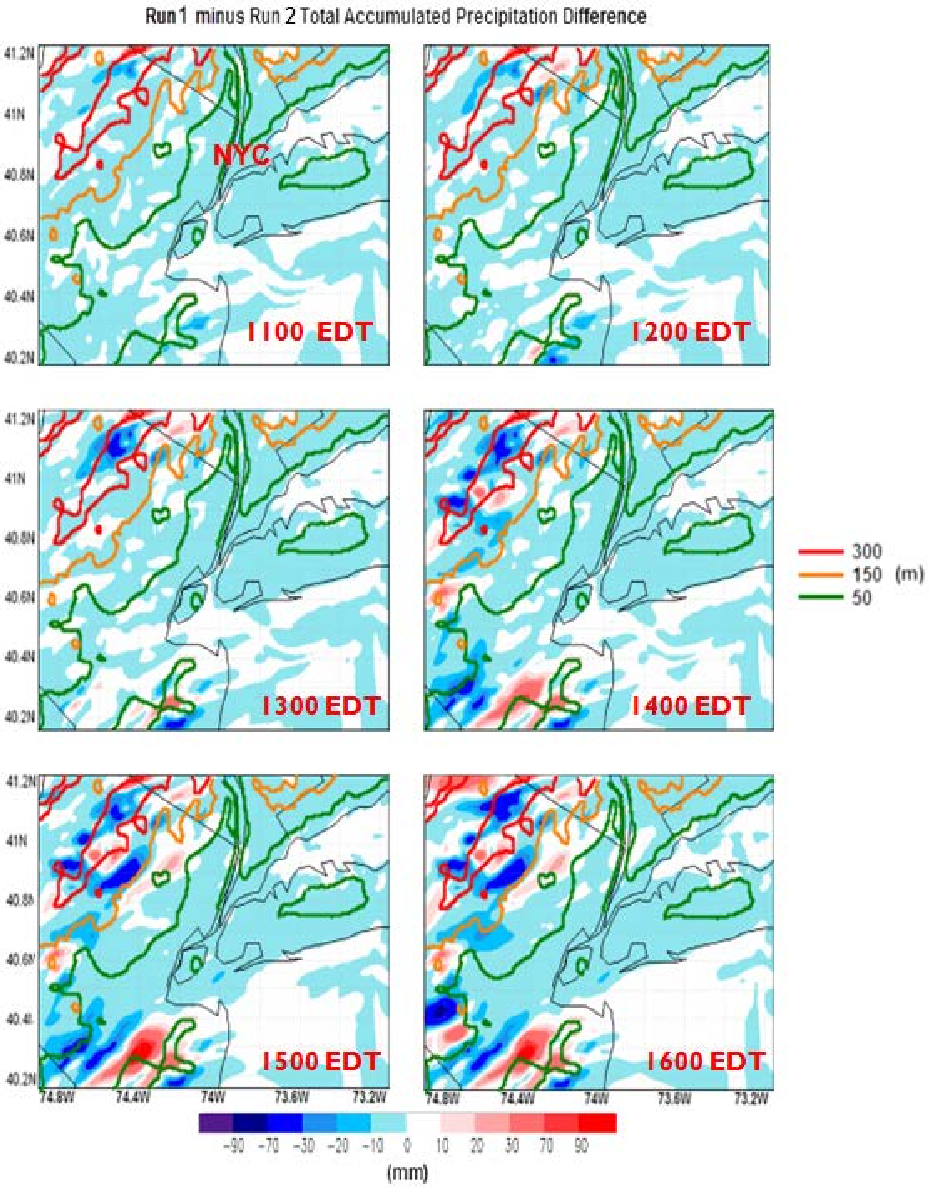




By 11 EDT, southerly flow turns into southeasterly sea-breeze over coastal NJ. Topo triggers moderate precipitation in north & south NJ. Light precip forms along the sea breeze front at 11 & 12 EDT (red lines). Convergence over hills at 12 & 13 EDT fuels precipitation to peak at 14 EDT. Rates decrease by 15 EDT, increasing again after 16 EDT, in the NW & SW. Total accum precip is highest in NJ (topo areas above 50 m), with less over NYC and points eastward.

11 July 2007 (localized) Precipitation Difference



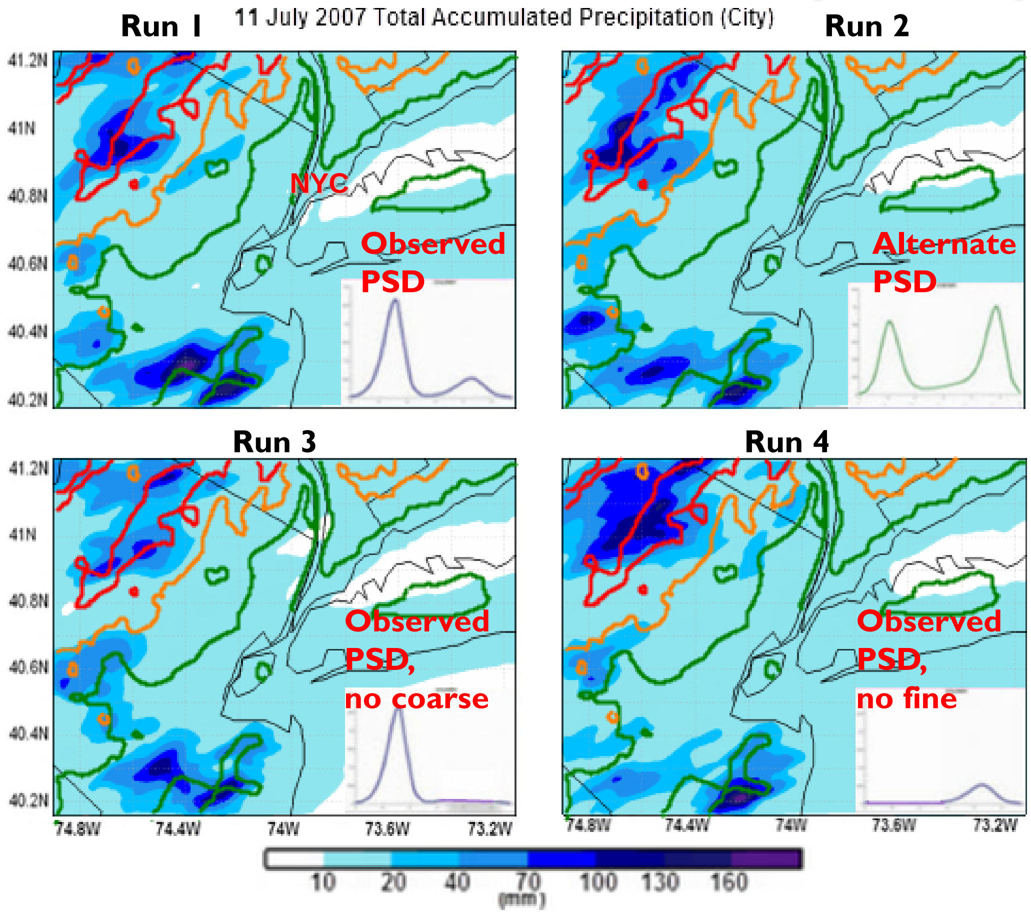


Total accumulated precipitation for both 11 July 2007 Runs above (Run 1 and Run 2. “Observed” here means that PSD for 11 July 2007 was used in the Run, “Alternate” means that PSD for 18 July 2007 was used).

Hourly total accumulated precipitation difference plots for Run 1 minus Run 2 are shown in the plot on the right.

Results how that the PSD switch enhances accumulation over most of the region (negative blues in Figs on right) because GCCN plays a greater role in speeding up precipitation than the smaller CCN. The exceptions (positive reds) are likely due to GCCN raining out quickly, allowing the CCN to produce more intense precip after they have eventually reached raindrop size.

11 July 2007 NYC PSD Variation
Total Daily Precipitation



Removal of the coarse mode leads to suppression in the region

High precipitation with the presence of both fine and coarse modes

Increased precipitation in North NJ with the presence of only the coarse mode

Conclusions

- PSD for July 2007 from AERONET were ingested into RAMS & was compared to a no-ingestion case. Results were improved when observed PSD was ingested, i.e., for 12/16 sites, bias errors were reduced (from an average of 19% without PSD, to 12% with PSD)
- Reduced GCCN number-concentration can result in increased GCCN-volume when the mode radius is large as is the case in 18 July 2007.
- Increased V-GCCN (18^{th}) enhanced precipitation at most locations over the region.
- Increased V-CCN volume (11^{th}) likewise suppressed precipitation.
- These last two effects are attributed to hastened/reduced rates of autoconversion due to the presence of larger/smaller particles, which enhances/impedes droplet coalescence rates, in agreement with Comarazamy et al. (2006) & Rosenfeld et al. (2008).
- PSD can impact the rate of autoconversion, and slow (fine mode) or quicken (coarse mode) the initiation of rainfall. Increasing the volume of fine-mode aerosol while removing the coarse mode results in reduced accumulated precipitation totals for 12/16 sites.

Things for the future…

- **Ingest spatially varying PSD.**

- **Use LIDAR data to understand the vertical aerosol structure.**

- **Investigate MODIS and GOES satellites for aerosol information, and learn how to ingest this information into RAMS.**

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Questions??

This study was supported and monitored National Oceanic and Atmospheric Administration (NOAA) under CREST Grant # NA11SEC4810004. The statements contained within the manuscript/research article are not the opinions of the funding agency or the U.S. government, but reflect the author's opinions.