Influence of cities on clouds, precipitation, and thunderstorms

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Outline re understanding urban-impacts on precipitation

- Where we are now
  - urban-atm Wx/Climate conflicts
  - urban-impacts on precip: proposed synthesis
- How we got here
  - data analysis
  - modeling
- Way forward
  - instrumentation
  - field studies
  - model inter-comparisons

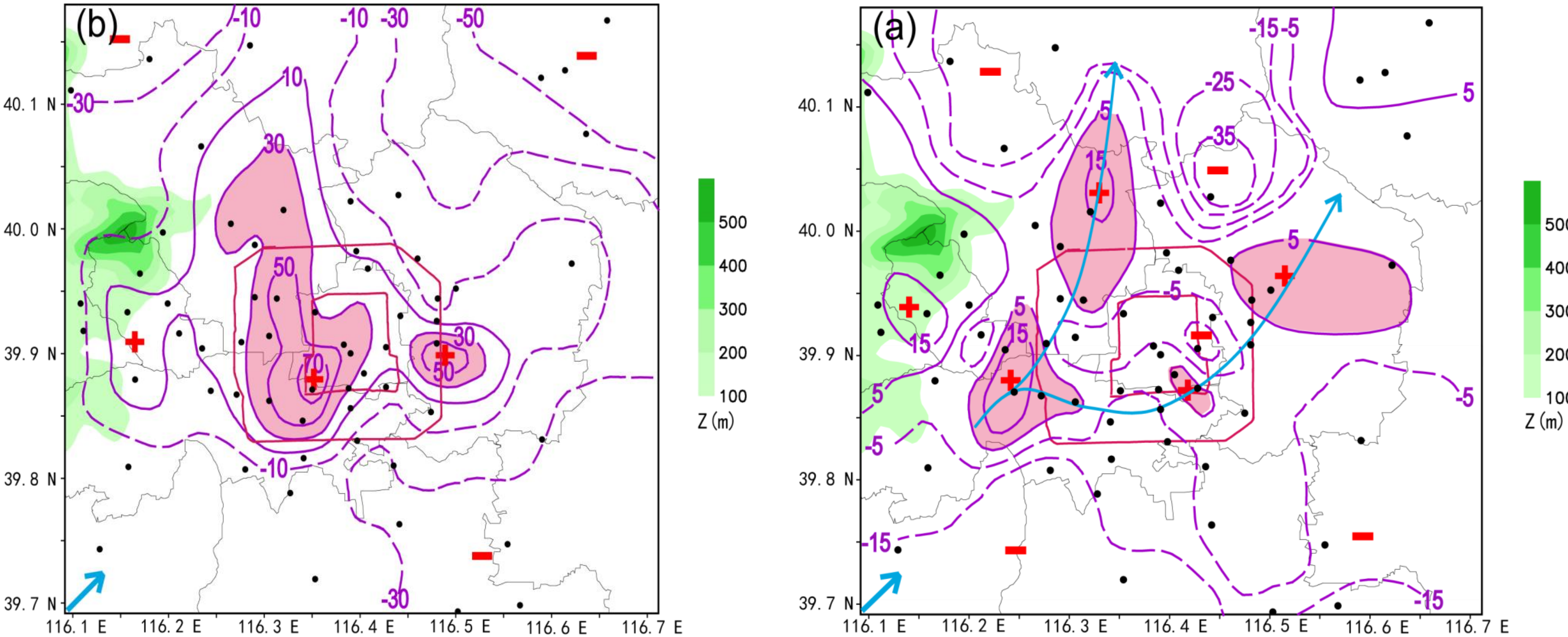
Background: Urban Wx/climate results from battles between conflicting urban-upsets to energy-, momentum-, & moisture-fluxes

> VISIBILTITY: decreased
> TURBULENCE: (mechanical & thermal) increased
> FRONTS (synoptic & sea breeze): slowed

> WIND SPEED: increased or decreased
> WIND DIRECTION: convergent or divergent
> PRECIP: increased or decreased
> THUNDERSTORMS: triggered or split

> SOIL MOISTURE: higher or lower than rural-values
> TEMP: increased (UHIs) or decreased (UCIs)

Here I/we are now: understanding urban (dynamics/impacts) on precip



Beijing IUM climo-precip study (red circles = ring highway roads)

- Data: Normalized (by regional-average) 2008-12 summer-total rainfall-amounts N(%) only for 850 hPa SW-wind cases (blue arrow) *for*
- *(left) UHI (≥ 1.25 ℃, 79 cases) → UHI storm-initiation → urban max*
- *vs. (right) no UHI (<1.25 ℃, 55 cases) → barrier storm-splitting → urban min*
- *1st test of Bornstein (2011) hypothesis with UHI-data*
- *Dou (her MS), Wang, Bornstein, Miao (2015) JAMC; Mon 11 AM in UCP1*

How did we get to Dou et al. via observational studies of summer convective thunderstorms: some key (of many) steps along the way

- 1970s: B. Atkinson's publishes London case studies
- 1970s: METROMEX studies in St. Louis
- 1980s: S. D. Chow's climatological studies in Shanghai
- 1980s: My climatological & case studies in NYC
- 1990s: My case studies in Atlanta during Olympics
- 2000s: M. Shepherd's summaries newer obs studies
- 2000s: New radar thunderstorm-obs
- 2000s: D. Rosenfeld: aerosol impacts on thunderstorms
- 2000s: D. Niyogi, M. Shepherd, et al. model urban thunderstorms
- 2010s: My work with S. Miao at IUM & J. Gonzalez at CCNY
- 2015: T. Oke, Mills, Christen, Voogt: new urban climate book
- Some few highlights of the journey

Prof. S. D. Chow (1988) of the East Normal U. produced excellent 1955-1978 climatology of Shanghai's "five islands" e.g., temp, RH, precip, in papers in *Acta. Scientia Sinica.* While climatological studies are good for, e.g., hydrological planning, without segmentation, they lack insight into causal-processes, as found in Dou et al.

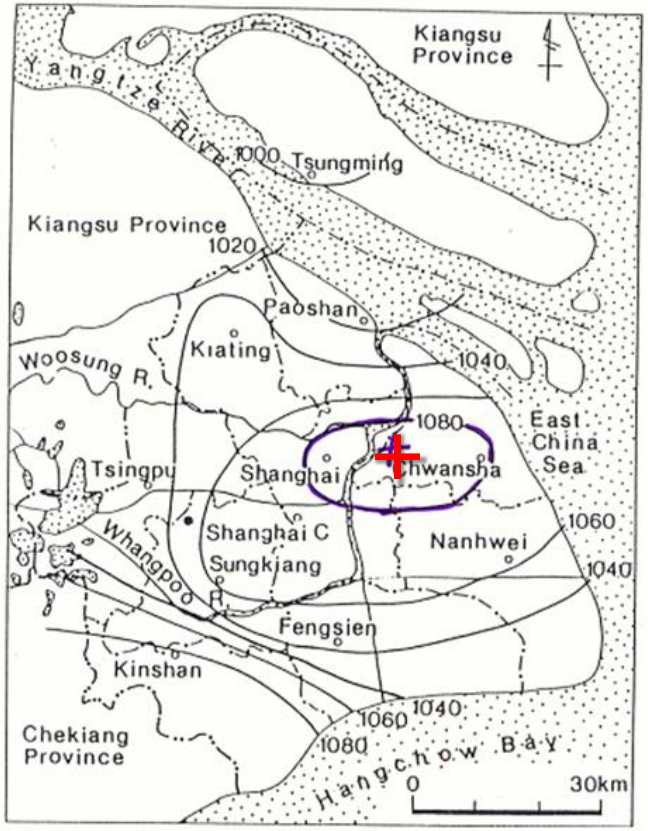


Figure 18. Mean annual precipitation over Shanghai districts (1959-1978).

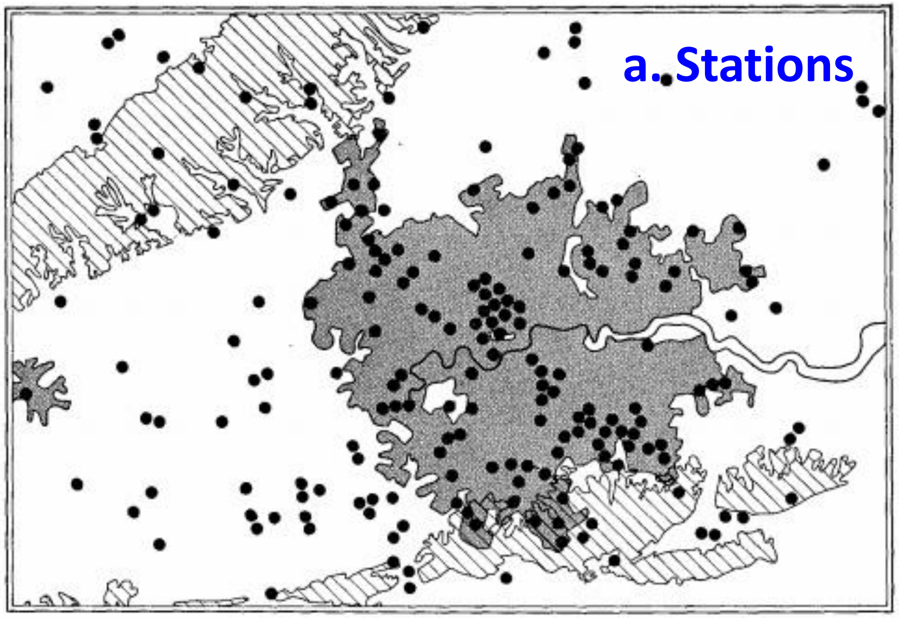


FIG. 3. Network of daily rainfall stations maintained by British Meteorological Office in London and environs. Rest of legend same as Fig. 2.

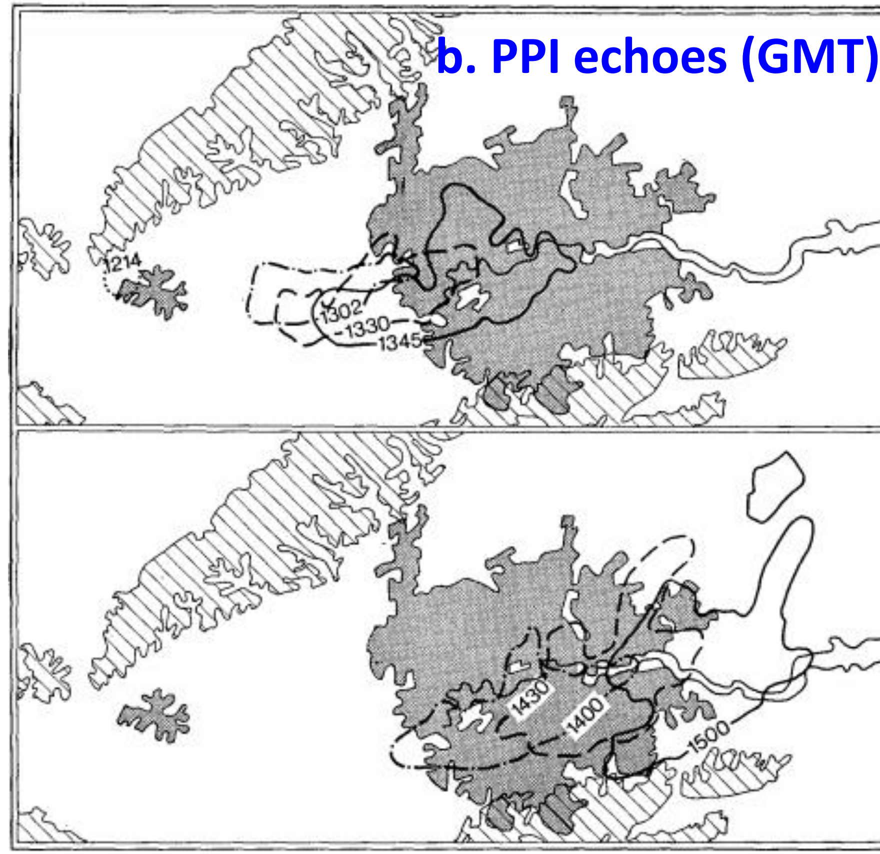


FIG. 5. Location of PPI echoes at different times (GMT) on 9 September 1955. Area ~130 km×65 km. Rest of legend same as Fig. 2.

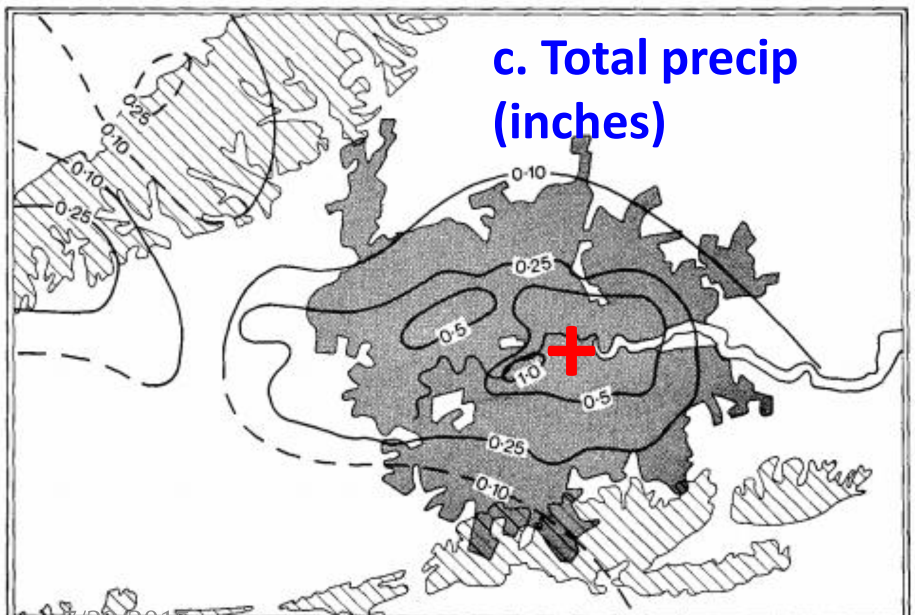


FIG. 4. Daily rainfall amounts in study area (inches) on 9 September 1955. Rest of legend same as Fig. 2.

- Early obs of clear daytime urban-initiated thunderstorm
- over (hot) London, 9/9/55
- Max precip > 1.0 inches
- Atkinson (1971) in JAM
- 3 other early cases: 1968-70

Observed METROMEX precip (cm) for

(a) 1971-4 total average-summer (Changnon et al. 1976) &

(b) 1971-5 total-summer during 21-24 CDT (Changnon et al. 1986)

Note: many people say cities produce a downwind precip-max, now in conflict with Bornstein (2011) & Dou et al.

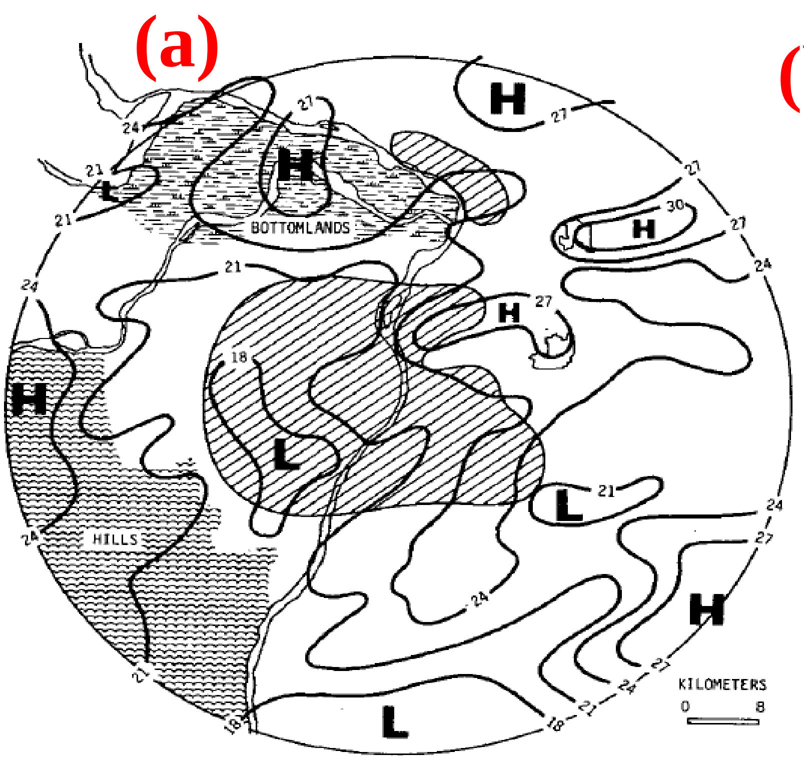


FIG. 2. Total average summer rainfall (cm) for 1971–74 period, in METROMEX network of 250 raingages.

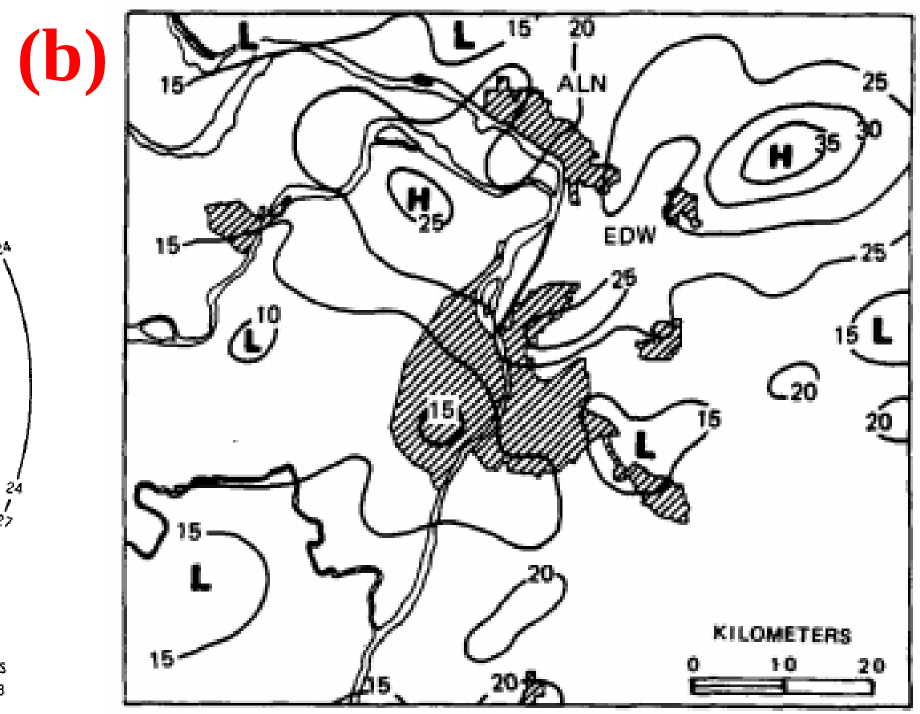


FIG. 2. Total summer rainfall (in centimeters) during 2100–2400 CDT in 1971–75. Hatched areas are major urban areas.

My path to thunderstorms (outline)

- 1960s: I'm Grad student on NYU/NYC urban-PBL project. I analyzed temp, moisture, & wind data from various sources
- 1970s: EPA grant to bring NYU/NYC data to SJSU; my students & I start to analyze it
- 1970s: We look at NYU data for sea breezes, & student notices synoptic & sea breeze fronts effected by NYC
- 1980s: When discussing these impacts at a seminar, NWS forecasters say that NYC splits thunderstorms and they give me two years of radar data to analyze

- Some of these research steps are in the next slides

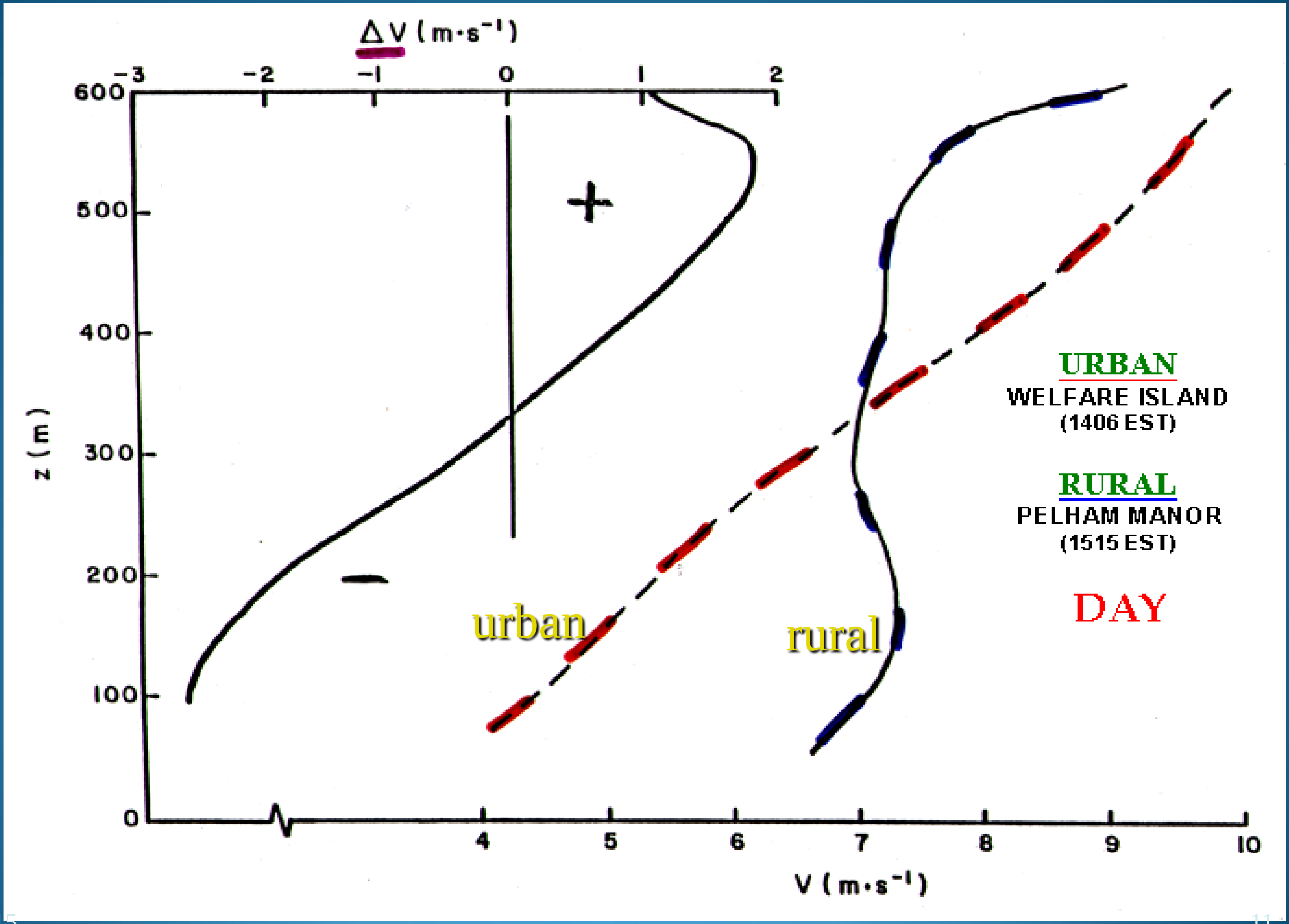
Parameter 1: Urban effects on wind speed
Bornstein and Johnson (1977)

- FAST SYNOPTIC-SPEEDS →
  SMALL UHI →
  URBAN Z_o DECELERATION

- SLOW SYNOPTIC-SPEEDS
  LARGE UHI → ACCELERATION INTO THERMAL-L

- CRITICAL BACKGROUND-RURAL SPEED ~ 3-4 m/s
  (NYC & London): next slide

OBS OF NYC DAYTIME URBAN-PBL ΔV (z)



No.-2: URBAN EFFECTS ON WIND-DIR

THE TWO EXTREME CASES:

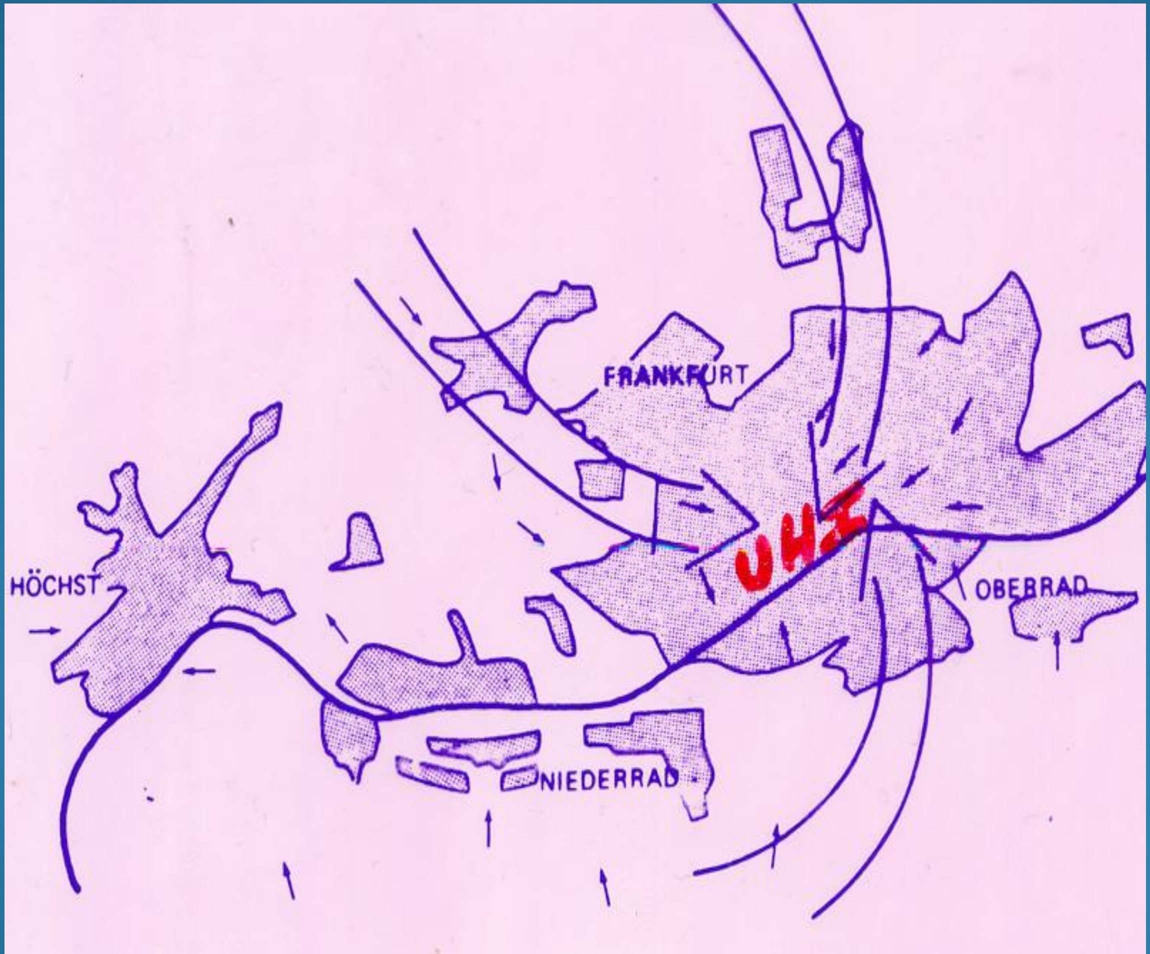
- SLOW SYNOPTIC-SPEEDS → LARGE UHI →
  LOW PRESSURE → CONVERGENCE INTO CITY
- FAST SYNOPTIC-SPEEDS →WEAK UHI →
  URBAN BUILDING-BARRIER EFFECT →
  FLOW DIVERGES AROUND-CITY

BUT WITH MODERATE SYNOPTIC-SPEEDS → CONVERGENCE ZONE IS ADVECTED TO DOWNWIND URBAN-EDGE

EXAMPLE (NEXT SLIDE)

NOCTURNAL UHI-INDUCED 10-m CONFLUENCE

a. In otherwise-calm synoptic conditions
b. With confluence center at Frankfurt urban center
c. A "golden case," with a clear sharp signal



Parameter 3: Urban effects on moving weather-fronts

- NYC data for (synoptic & sea breeze) fronts

- Two conflicting urban effects
  - building-barrier effect retards frontal- movement
  - & UHI effect accelerates frontal-movement

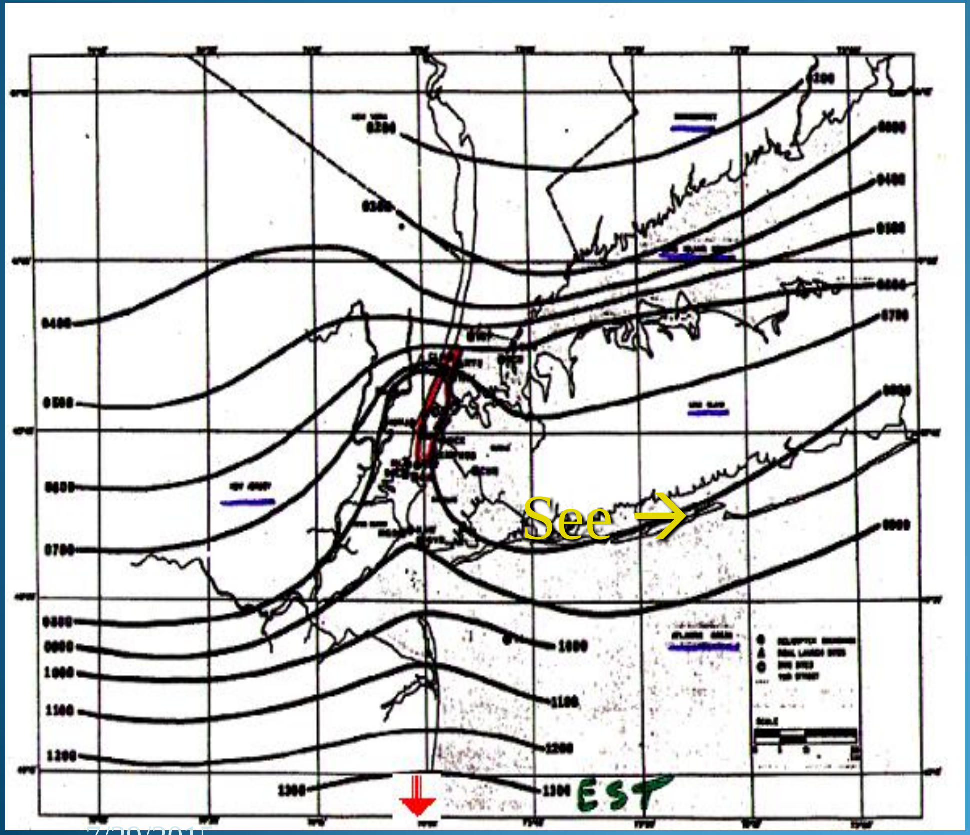
- Two examples follow

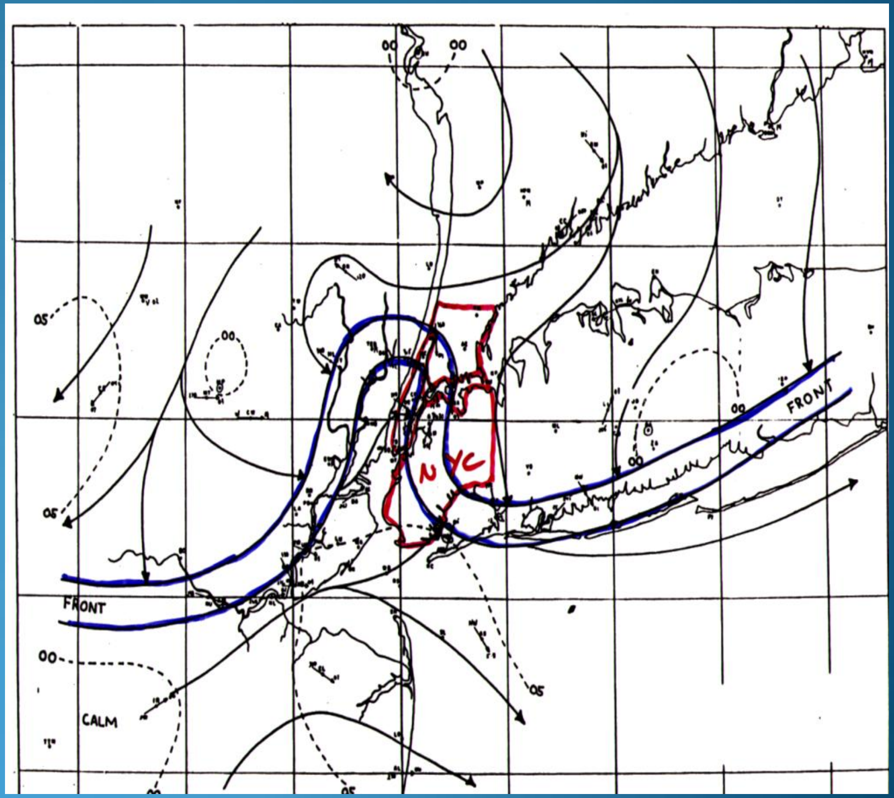
- Loose and Bornstein (1977) &
  Gaffen and Bornstein (1988)

Weak cold-frontal (N to S) passage over NYC

a. Hourly positions (left) based on 10-m wind directions

b. At 0800 EST (right): T, q, & SO_2 z-profile-changes showed lowest 250 m of atm not-replaced, as front "jumped" over city. Also a golden case.



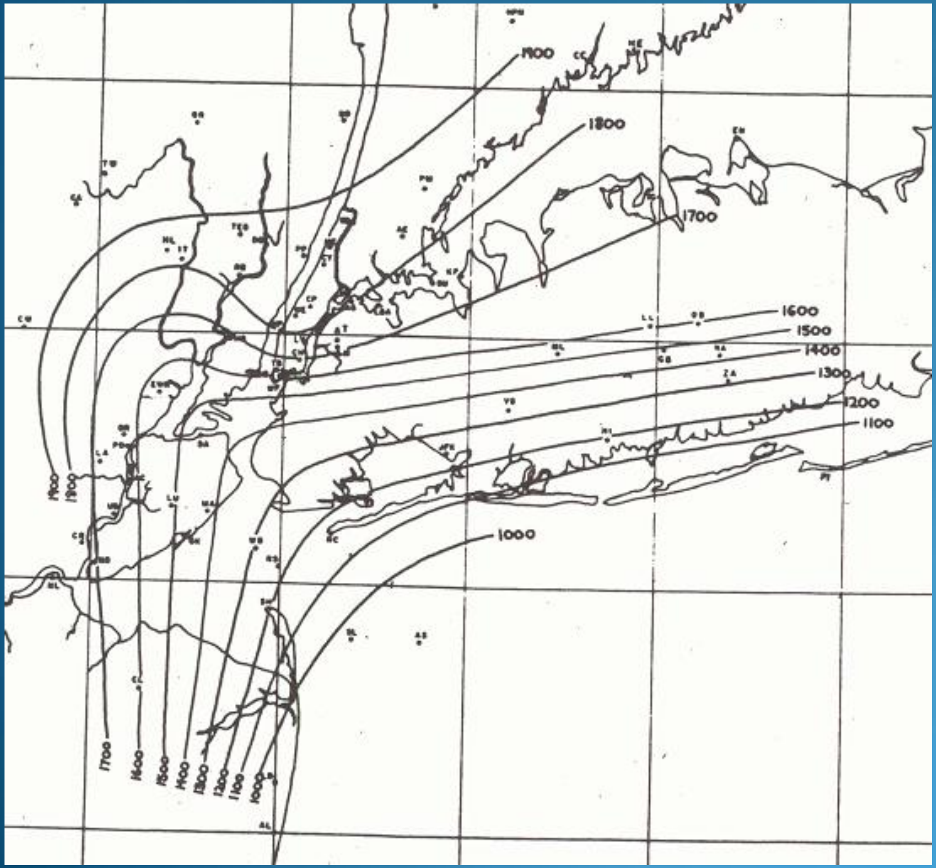


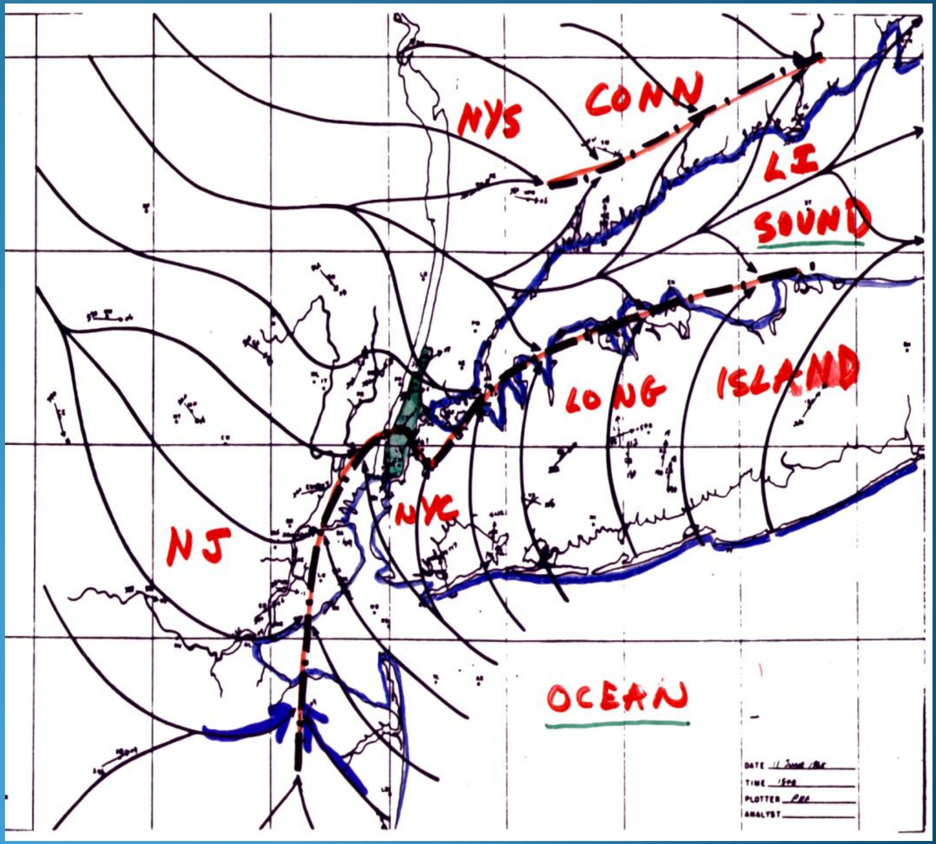
Sea-breeze frontal (S to N) passage over NYC: 9 March 1966

a. hourly positions (left) shows urban retardation

b. 1800 EST (right): note urban-induced retardation bulge

c. Another golden case (term from Dev Niyogi)

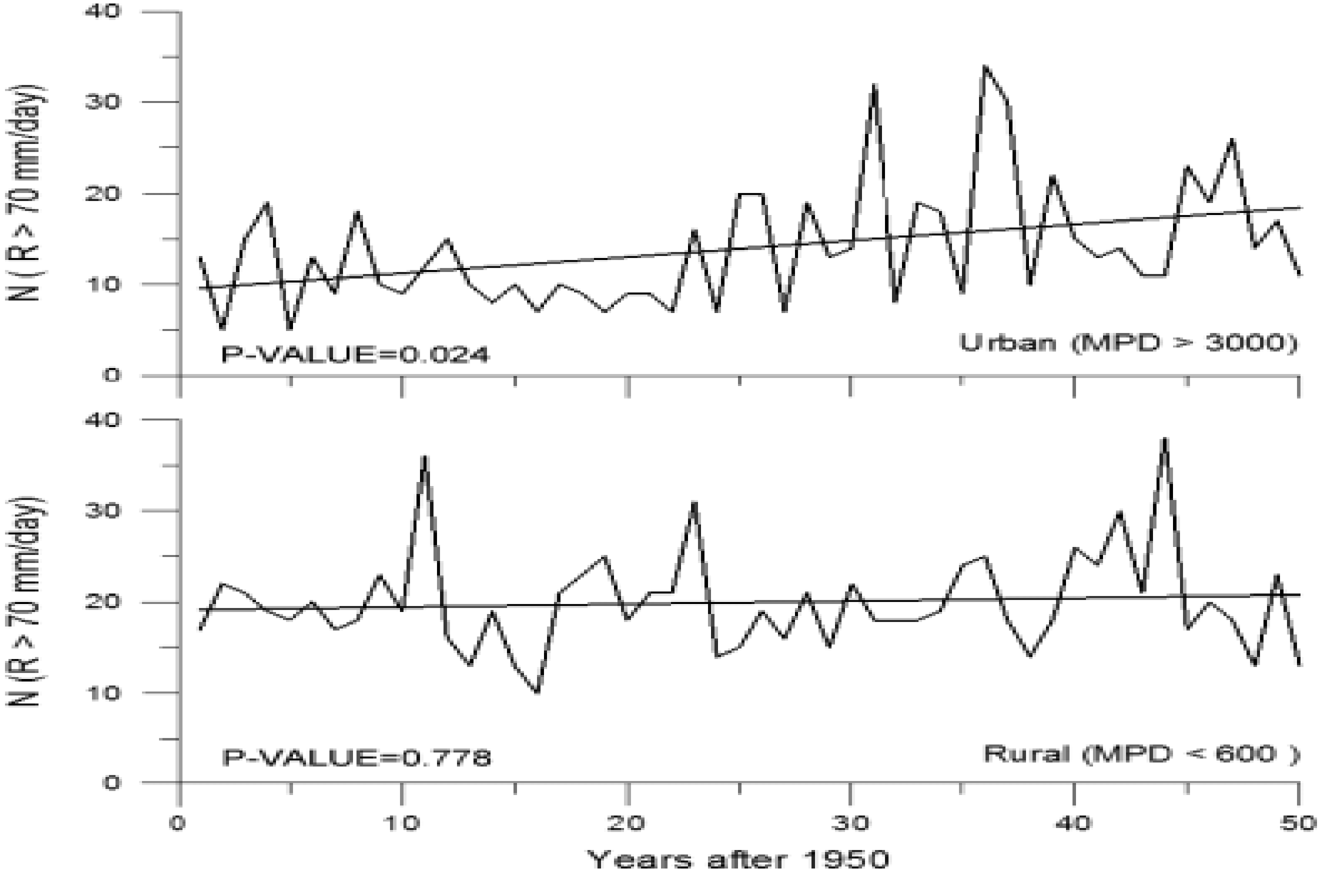




(Last) Parameter 4: Urban-impacts on summer thunderstorm-precipitation

- THERMODYNAMICS: SFC-TEMP → HORIZ. WINDS → VERTICAL WINDS → THUNDERSTORM PRECIP. → FLOODING??
- IF URBAN PRECIP. IS WELL SIMULATED/UNDERSTOOD, THEN EVERYTHING BEFORE SHOULD BE CORRECT
- URBAN THUNDERSTORMS ARE A CHALLENGE TO STUDY, DRAMATIC, & DANGEROUS TO LIFE AND PROPERTY
- CURRENT THERMODYNAMIC SYNTHESIS IS SHOWN IN NEXT SLIDE
- AFTER THERMODYNAMIC IMPACTS, AEROSOLS MODIFY PRECIP. (DISCUSSED BELOW)
- NYC, ATLANTA, BEIJING STUDIES: FOLLOWING 4 SLIDES

Heavy rainfall upward trend over India only noted in urban areas, i.e., population densities > 3000 from Kishtawal et al. (2010) in IJOC (courtesy of D. Niyogi)

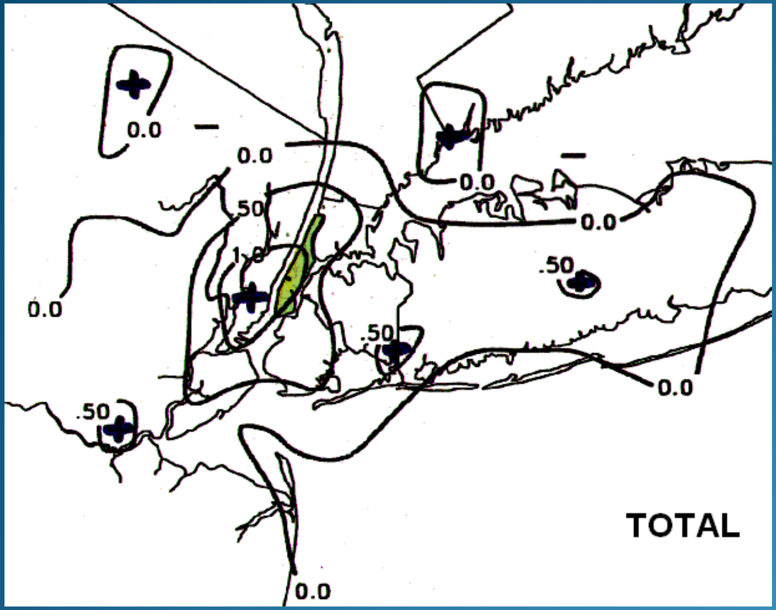


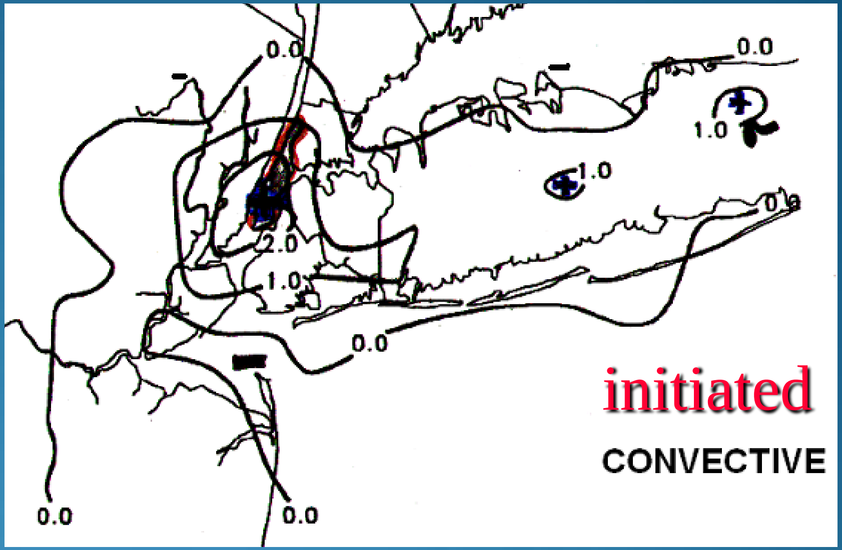
Bornstein (2011): Current hypothesis of thermodynamic impacts of urban areas on thunderstorms (two ideal, extreme-cases); aerosols have secondary effects (discussed below), but only after storm-modification or -formation; 3 examples follow

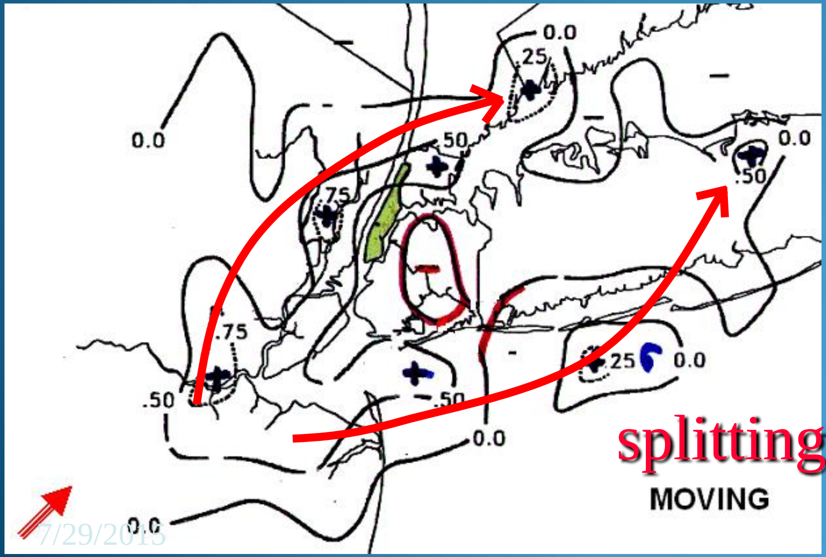
Synoptic conditions	UHI mag-nitude	Urban winds	Urban impacts on storm move-ment	Urban precipitation pat-tern
Total regional cloud–cover, storms, & fast winds	Small	Diverge around city	Storm diverges/ bifurcates around city	➢ Lateral-max along diverging streamlines ➢ Min over city & down-wind in urban rain-shadow
No regional clouds or storms, & slow winds	Large	Converge into low - pressure over city	Storm forms over city	➢ Max over city

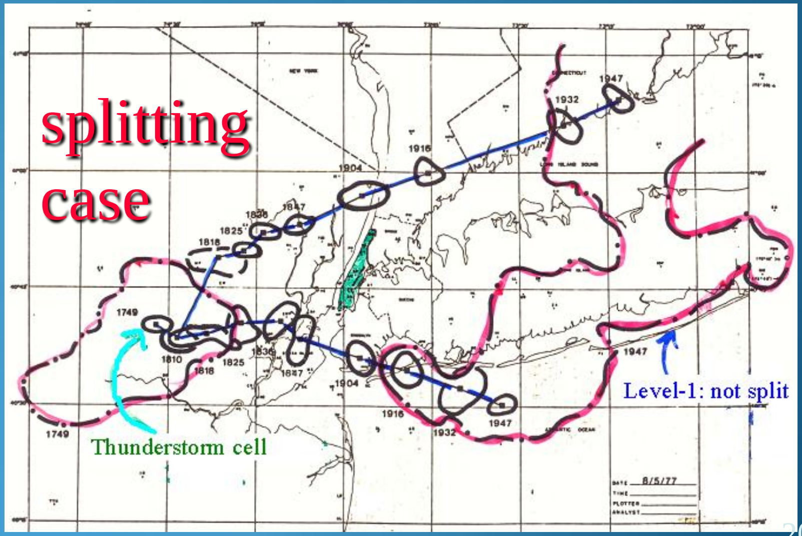
e.g., NYC 2-years summer day: thunderstorm/precip radar-echos (σ's re uniform-distribution) for cases: total = convective + moving

Bornstein & Leroy (1985)









ATLANTA SPLITTING-STORM CASE-STUDY

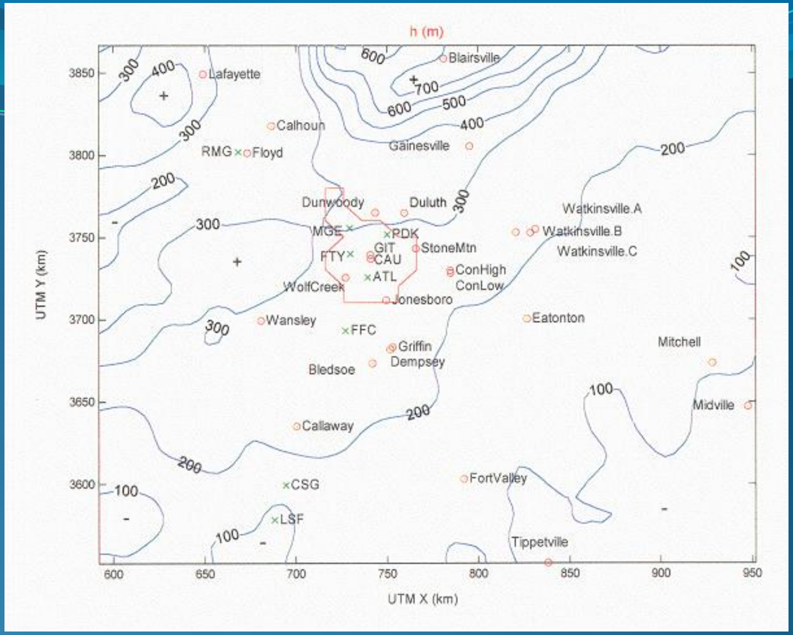
A. OB SITES (RIGHT)

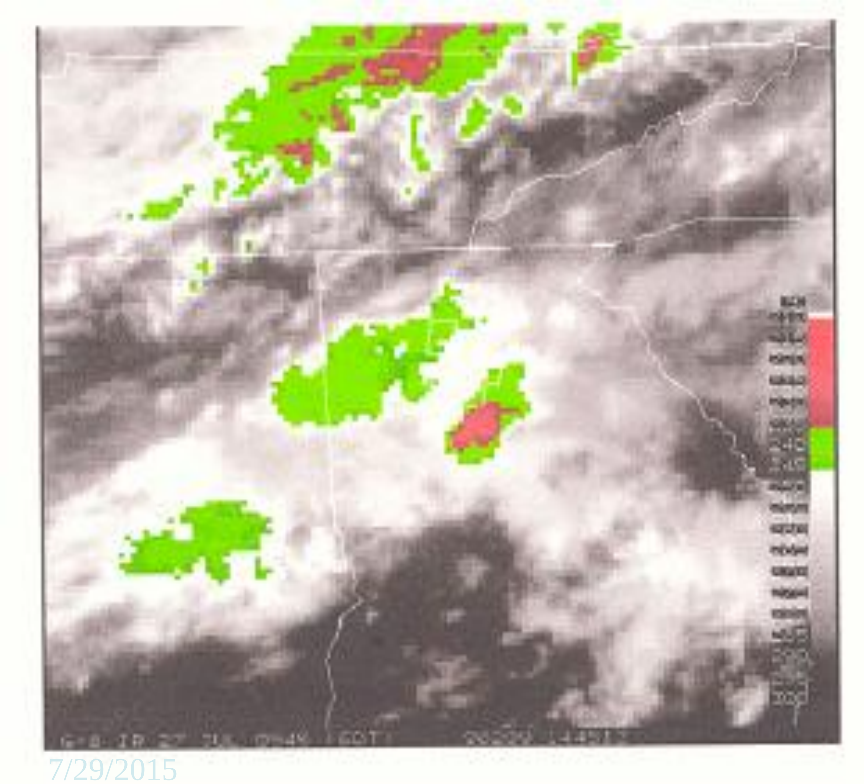
B. SATELLITE OBS (BELOW)

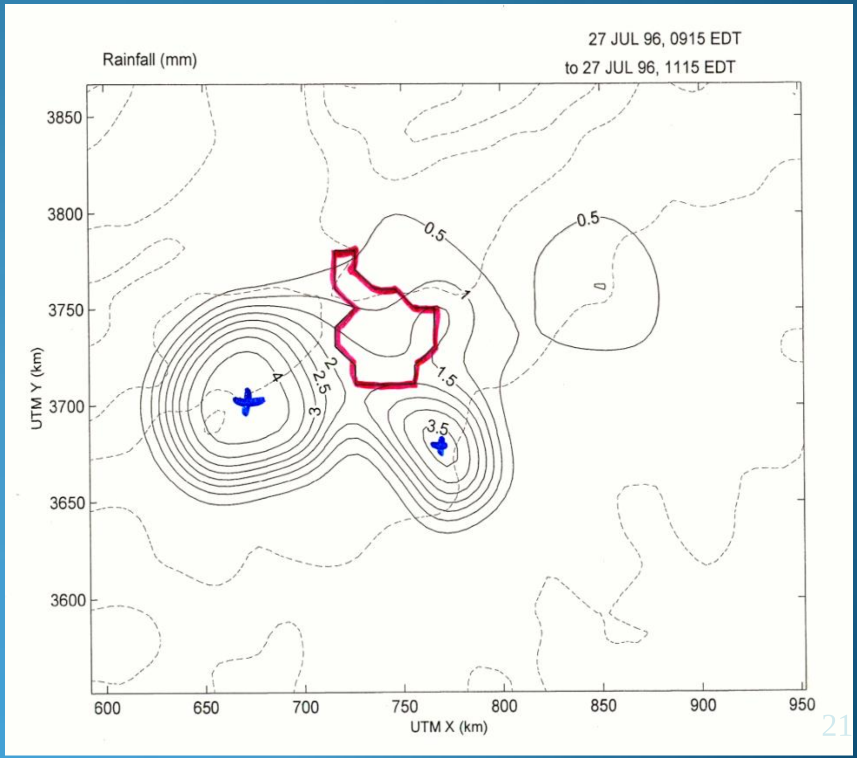
C. SFC PRECIP OBS (LOWER R)

BORNSTEIN & LIN (2000)

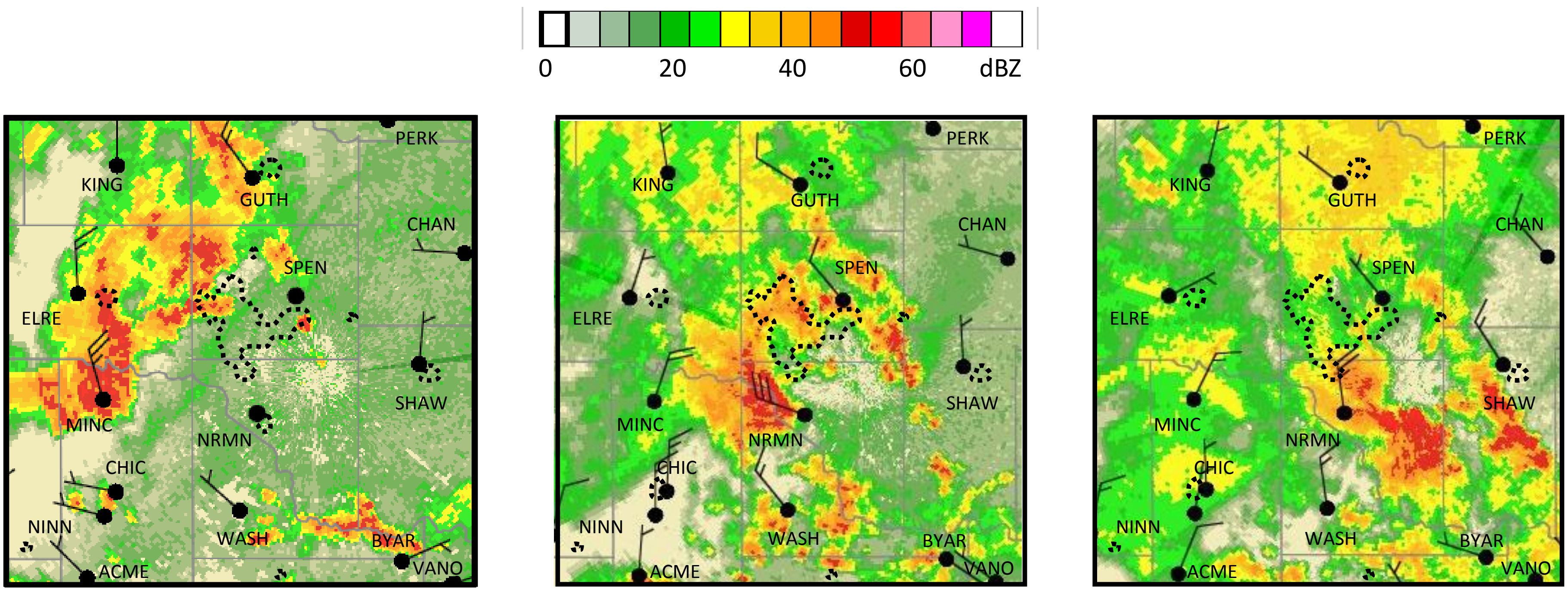
D. A GOLDEN CASE







A thunderstorm that split over Oklahoma City (Niyogi et al. 2006, JGR)



1015 UTC 1100 UTC 1130 UTC

Observed base-reflectivity (dBz, colors) from OKC Radar, representing a nest-4 (1.33 km) COAMPS simulation. Dashed-outline represents OKC's downtown urban-area. Observed surface winds (full barb = 5 m/s), from OK Mesonet-stations, show bifurcating winds (in central panel)

New 2011 Beijing rainfall case-studies (J. J. Dou)

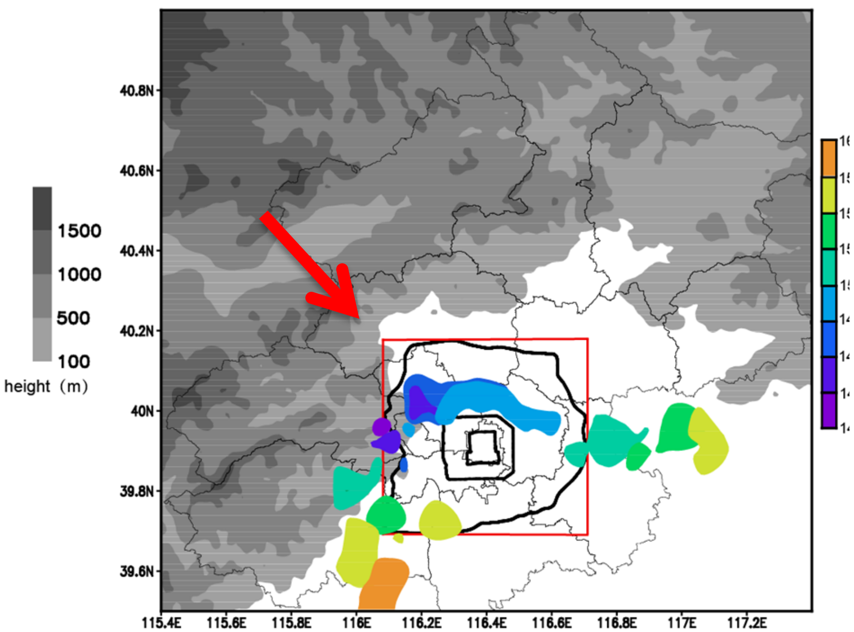
> Red box is domain on previous slide

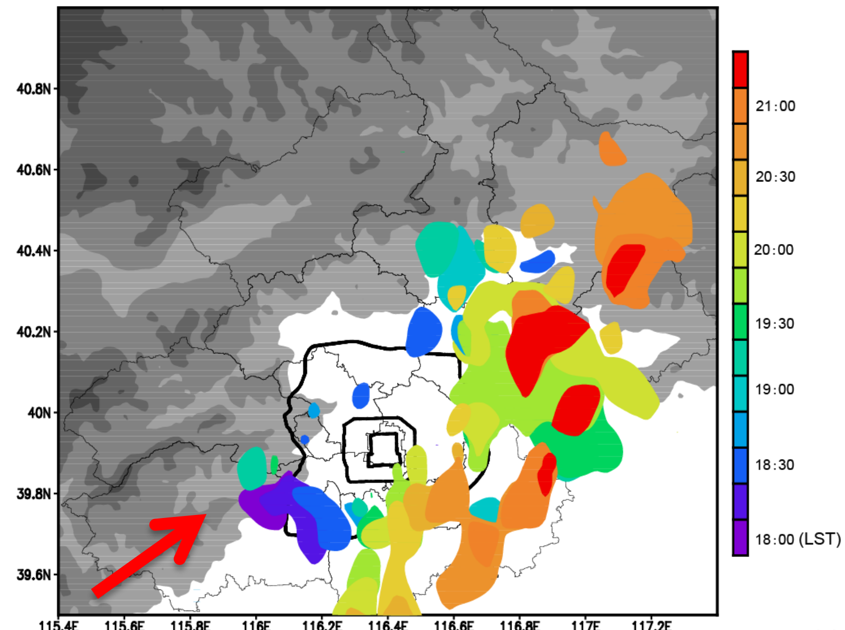
> (Left) 8 July storm from NW (colors: areas with precip > 3-mm/ 15-min), results show bifurcation

> (Right) 24 July storm from SW (colors: areas with precip >15-mm/ 15-min, results show only deflection (to right in this case)

> Question: what part of climo-study was sum of deflection-cases?

> Two golden cases

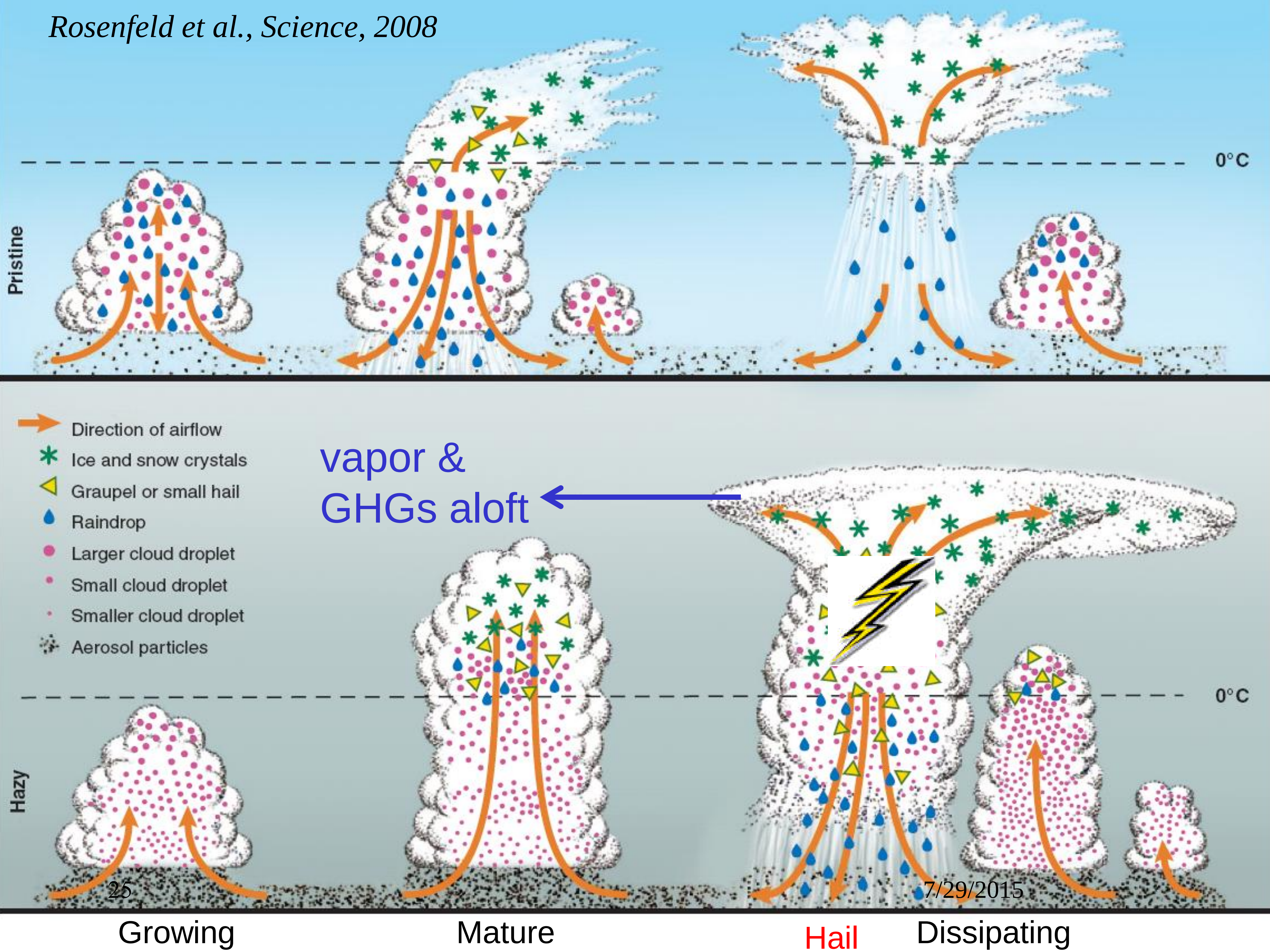




Aerosols generally affect thunderstorms in two ways (Rosenfeld 2008, 2015):

1. direct radiative-effects on
   a. surface/atm energy balances
   b. atm stability
2. cloud microphysical-effects (see next 2 slides)

Note: Rosenfeld agrees that urban aerosols have secondary effects on urban precipitation timing, duration, and amounts, but only after urban storm-bifurcation or initiation



Rosenfeld et al., Science, 2008
0°C
Pristine
Direction of airflow
Ice and snow crystals
Graupel or small hail
Raindrop
Larger cloud droplet
Small cloud droplet
Smaller cloud droplet
Aerosol particles
vapor &
GHGs aloft
0°C
Hazy
Growing
Mature
Hail
Dissipating

Post-2002 Urban Precip Studies (except Bornstein & Lin 2000)
Shepherd & Mills (2011), a great review-paper

Paris, Multiple European Cities: Thielen et al. 2000, Trusilova et al. 2008, Freud 2008

China: Jin, Shepherd, and King 2005, Jin and Shepherd 2009, Meng et al. 2007, Kaufmann et al. 2007, Zhang et al. 2007, Guo et al. 2006, Jin and Shepherd 2008, Zhang et al. 2008, Zhang et al. 2009

Atlanta, St. Louis, Phoenix, Houston, Baltimore, Dallas, Oklahoma City, Indianapolis St. Louis, New Jersey Fairbanks: Bornstein and Lin 2000, Shepherd et al. 2002, Rozoff et al. 2003, Burian and Shepherd 2003, Shepherd et al. 2004, Molders and Olson 2004, Dixon and Mote 2003, Diem and Brown 2003, Burian et al. 2004, Diem and Mote 2005, Burian and Shepherd 2005; Shepherd 2006, Niyogi et al. 2006, Mote et al. 2007, van den Heever and Cotton 2007, Ntelekos et al. 2007, Rose et al. 2008, Diem 2008, Wichansky et al. 2008, Shem and Shepherd 2009, Zhou and Shepherd 2009; Stallins et al. 2009, Bentley et al. 2009; Lacke et al. 200; Pyle et al. 2009)

Mexico City, Sao Paolo: Farias et al. 2009, Aiken et al. 2009, Landulfo et al. 2005

India, Kolkata, Saudi Arabia, Cairo: Robaa et al. 2003, Shepherd 2006, Mitra et al. 2008, Kishtawal et al. 2009

Japan, Taiwan, Korea: Ohashi and Kida 2002, Fujibe 2003, Inoue and Kimura 2004, Ikebuchi et al. 2007, Chen et al. 2007, Han and Baik 2008, Matheson and Ahie 2008

Sydney: Gero and Pittman. 2006

Le Grande Summary for Urban Obs

- Main lesson: Estimation of true-magnitudes of urban-induced weather/ climate changes requires “segmented” data-analyses (e.g., by wind dir. & UHI-mag.) or else
- you obtain only small-differences between compensating urban-impacts
- You must use “intuition” to ask correct question i.e., how to segment your data, based on your meteorological knowledge

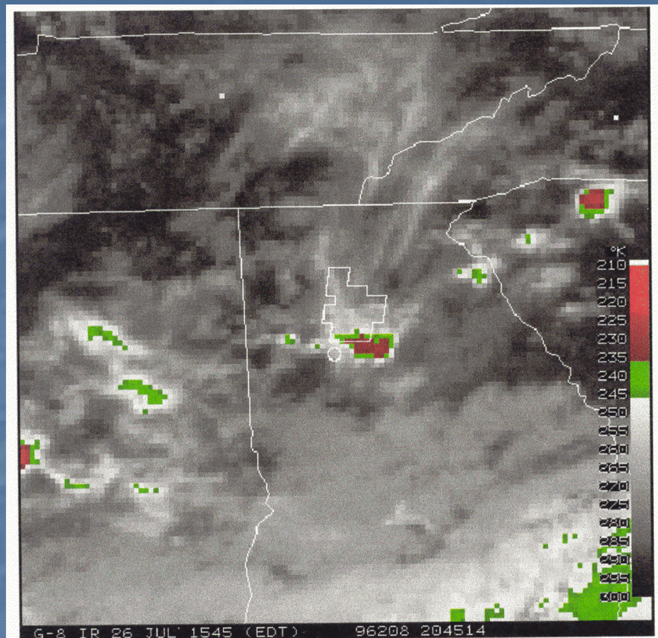
OVERVIEW of Part 2: Precip modeling

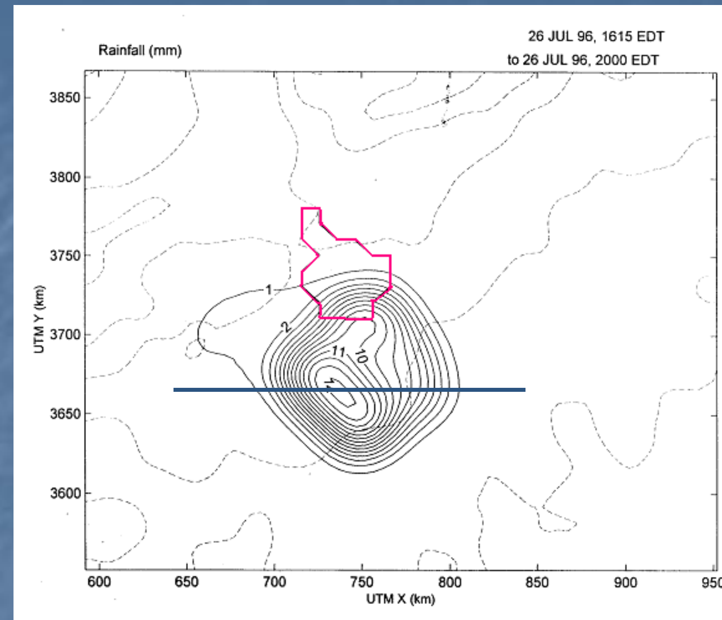
- Evolution of urban meso-met models:
  - Formulations
  - Urban Precip Case-studies
    - Pre uWRF (two)
    - With uWRF (one)

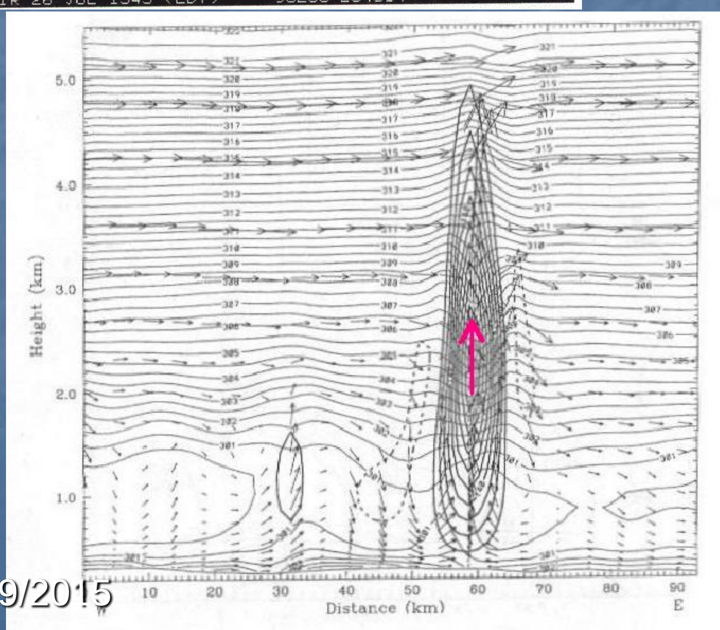
- Future urban meso-met models

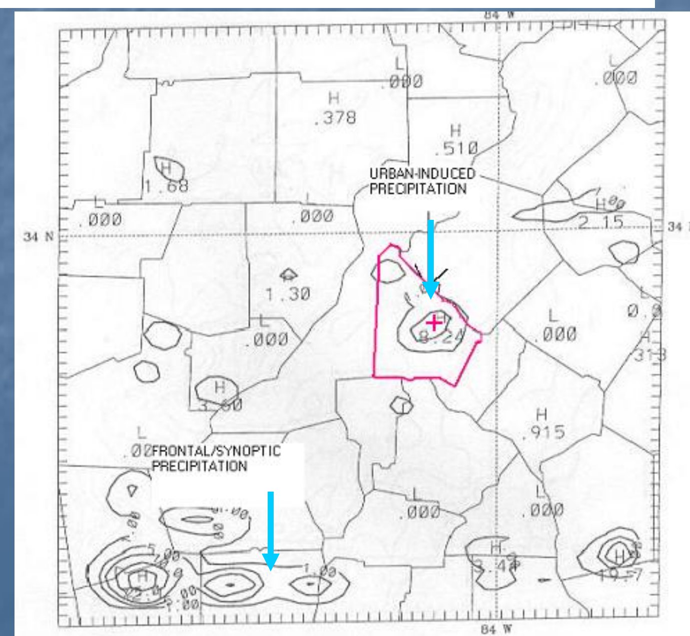
- Conclusions

Case 1. ATLANTA UHI-INITIATED STORM: OBS SAT & PRECIP (UPPER); & MM5 w (m/s) & precip (cm) (LOWER), Craig (2002), golden case

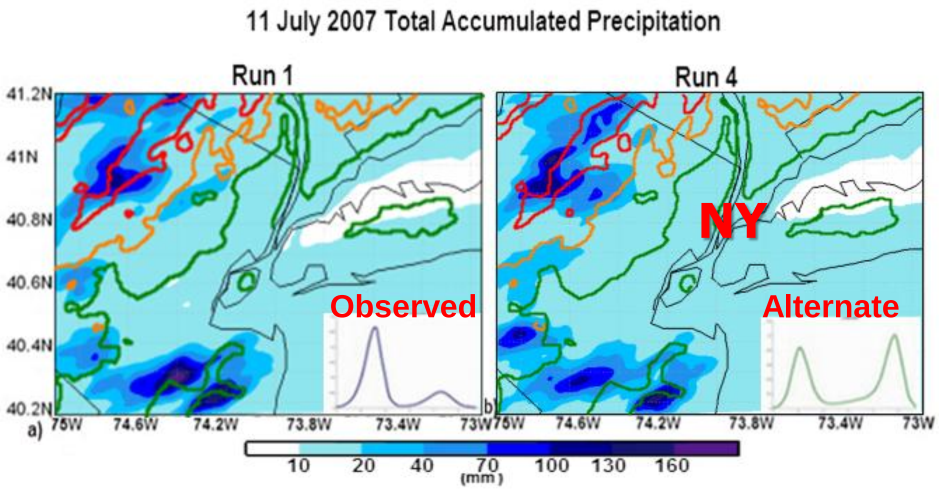


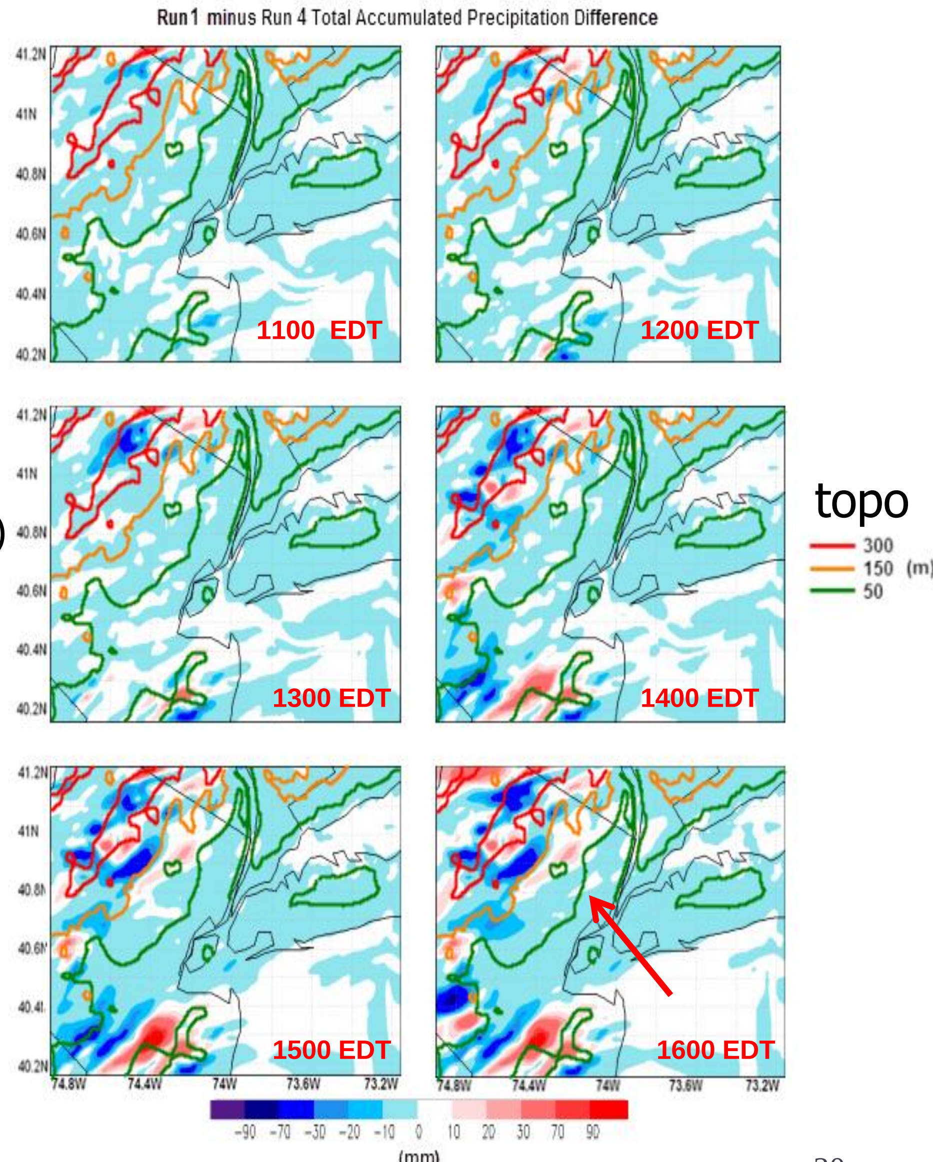






Pre Case 2: Aerosol-induced precip-impacts over NYC (storm from SE brought clean-air) Hosannah et al. (2013) at CCNY





>Above: Total-accumulated precip (mm) for Run 1 (Observed CNN) & Run 4 (Alternate: extra GCNN) Particle Size Distributions (PSDs)

> RAMS (not WRF): better aerosol-physics

> Note: Topo (thin colored lines) initiates precip

> At right: Hourly total-accumulated (mm) precip-differences (Run 1 minus Run 4)

> So GCCN: reduced-precip (red) near-field & enhanced-precip (blue) far-field

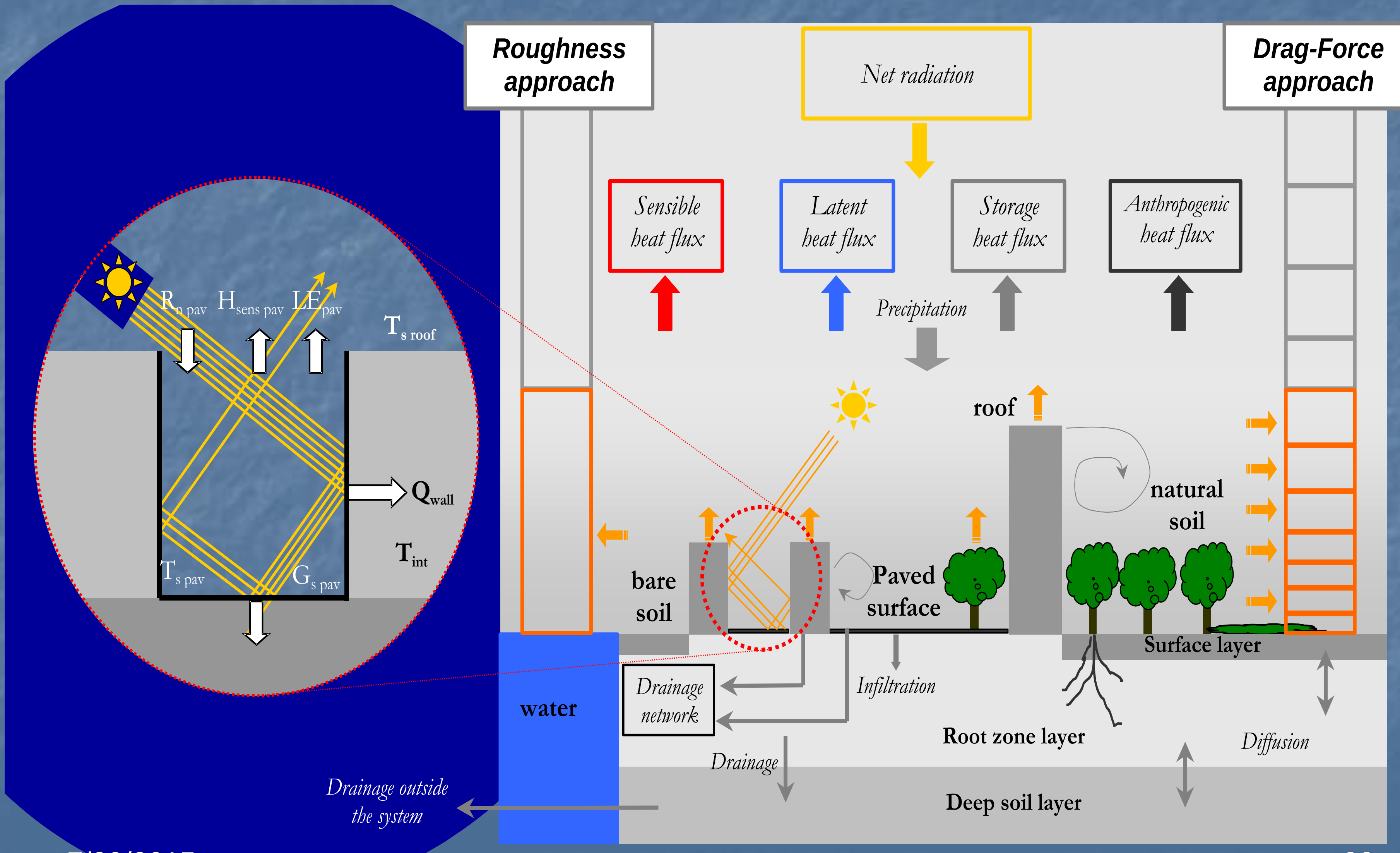
> Results fit theory of D. Rosenfeld

> Note city vs. no-city runs also showed impacts

Current Complex Urban Meso-Met Wx Models (e.g., uWRF)

- NCAR/WRF has 30-K users world-wide
- uWRF has sophisticated-modifications to
  - Canyon energy-budget → stronger UHIs
  - Porous-flow building-barrier parameterization as f(x,y,z) → enhanced speed-reductions
  - z_0 does not parameterize buildings, e.g., simple models add displacement-depth d
  - New PBL prognostic-Eqs for: T, V, q, & TKE
- uWRF used at: e.g., NCAR; IUM, SJSU, CCNY, CIEMAT, Altostratus, Inc.
- Formulation + 2 case-studies follow

uWRF: Mason canyon-energy + Martilli PBL (developed within my TVM/URBMET model

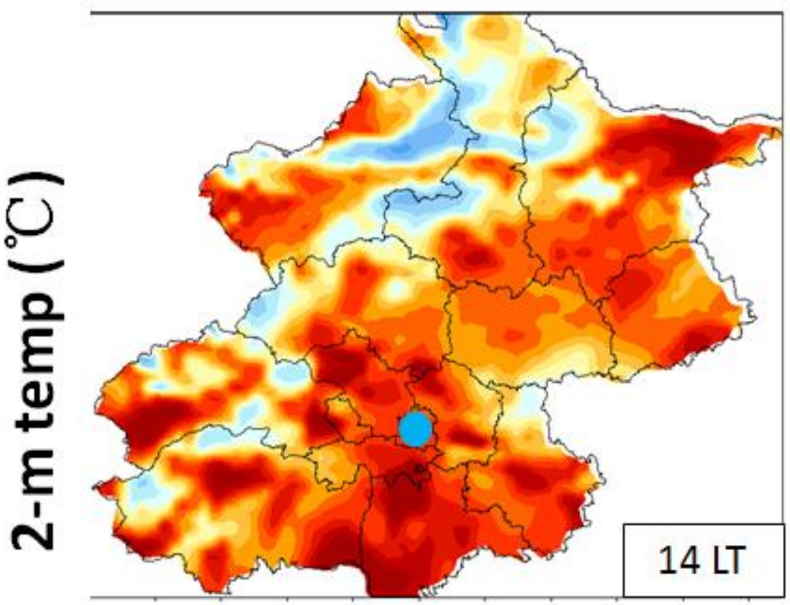


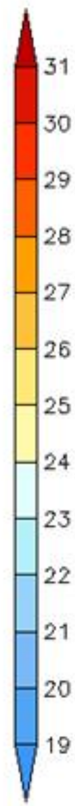
Study-1: IUM u_1WRF (1-level urbanization) simulations of the 23 June 2011 Beijing squall-line

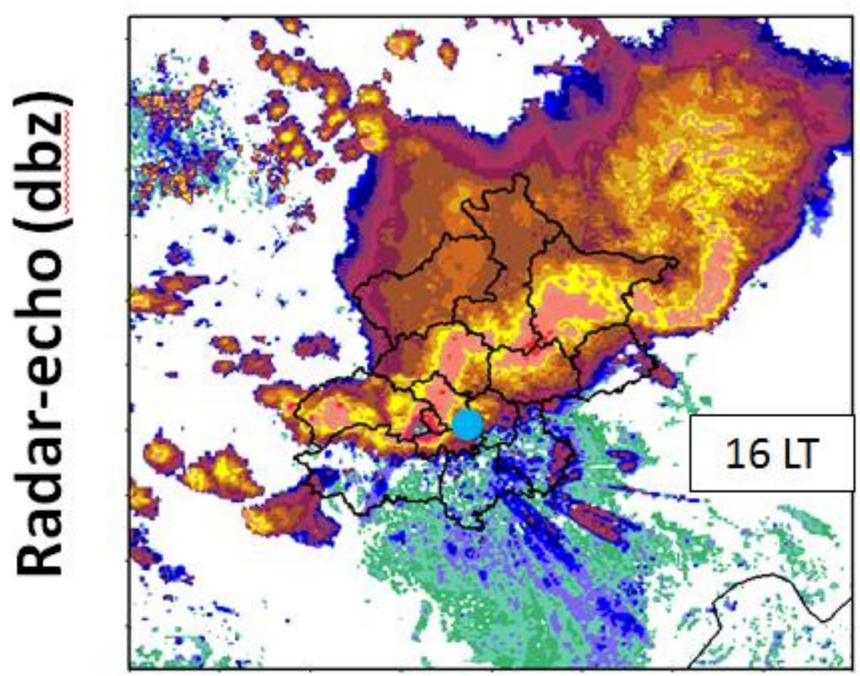
Yizhou ("Derek") ZHANG (PhD thesis) at IUM

Notes: (a) Black-lines are Beijing district-boundaries; city center is ●

(b) Weak-UHI (right) exists just as rain reaches Beijing (left)

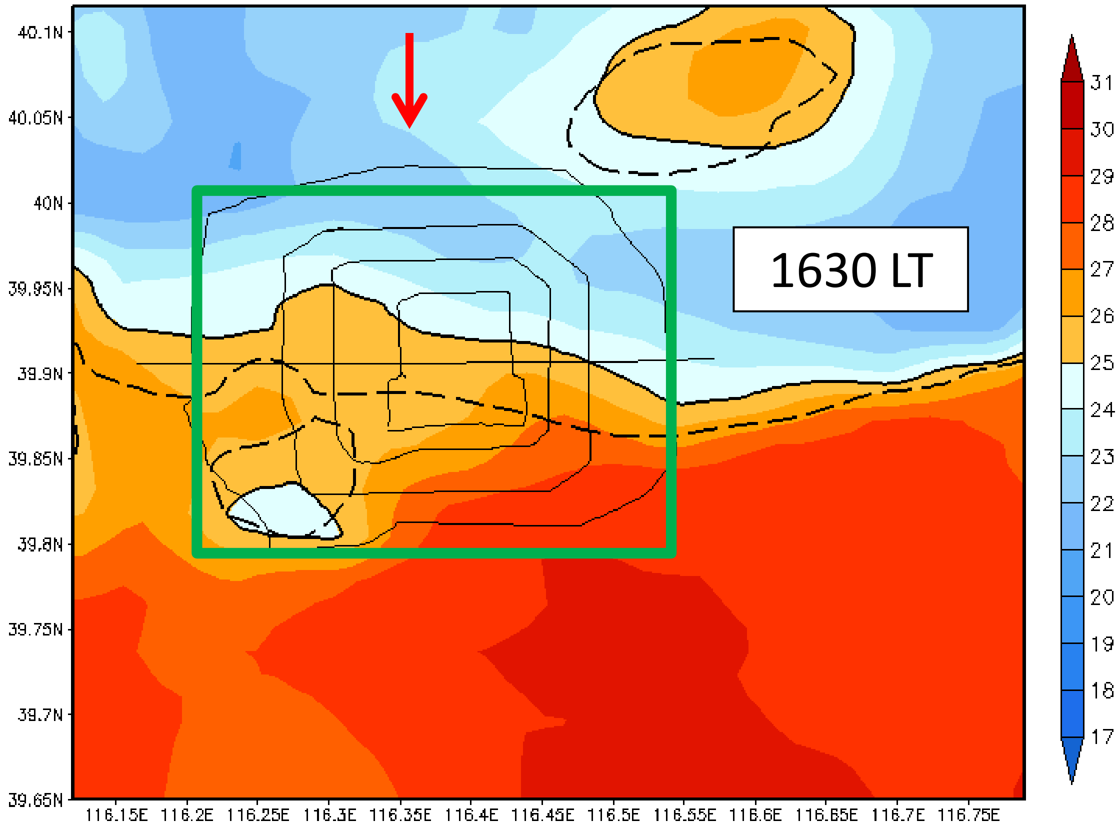






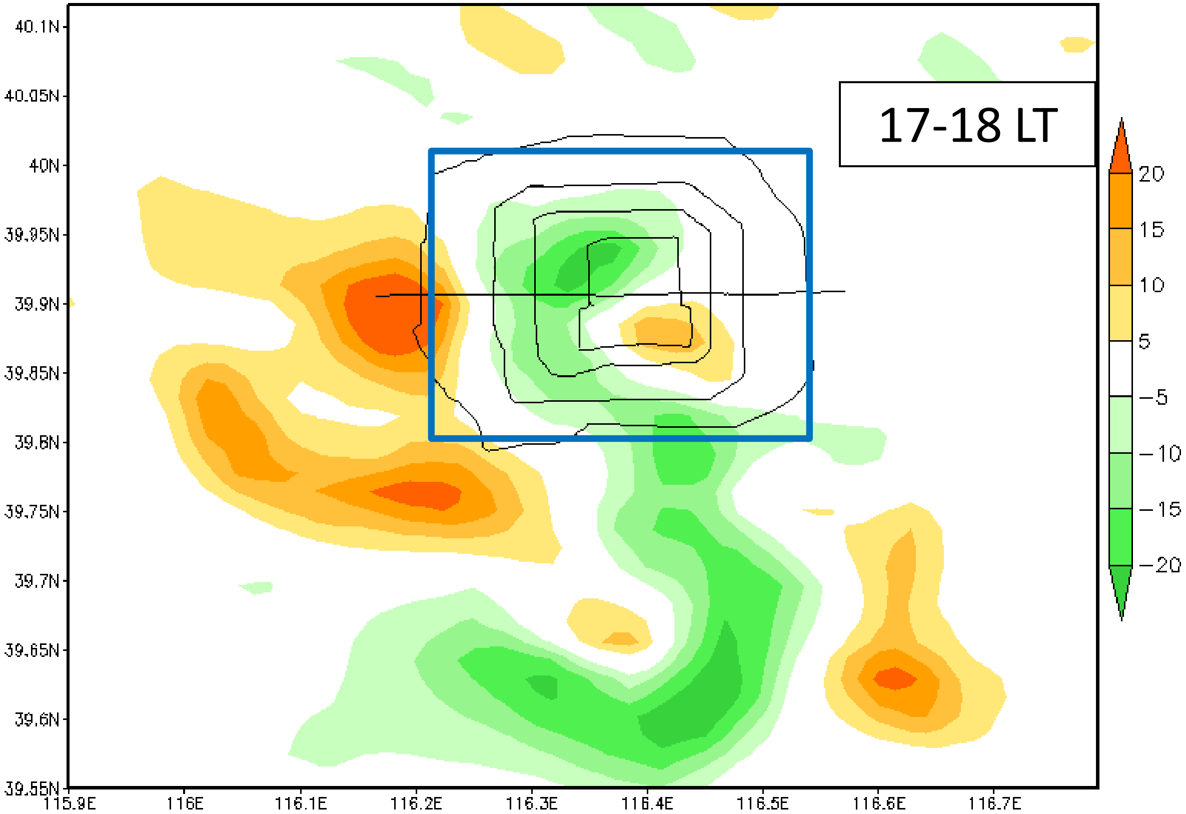
Squall-line southward (↓)speed-of-movement

- Beijing: within green box; thin-circles are 4 of its ring roads
- Colors: simulated 2-m Temp, with 25°C as "boundary"
- u_1WRF squall-line movement over city (solid line) is "**slowed**" a bit" by large urban z_0 vs. WRF (no-urban) case (lower dash-line)
- Reduced slowing in adjacent rural-areas

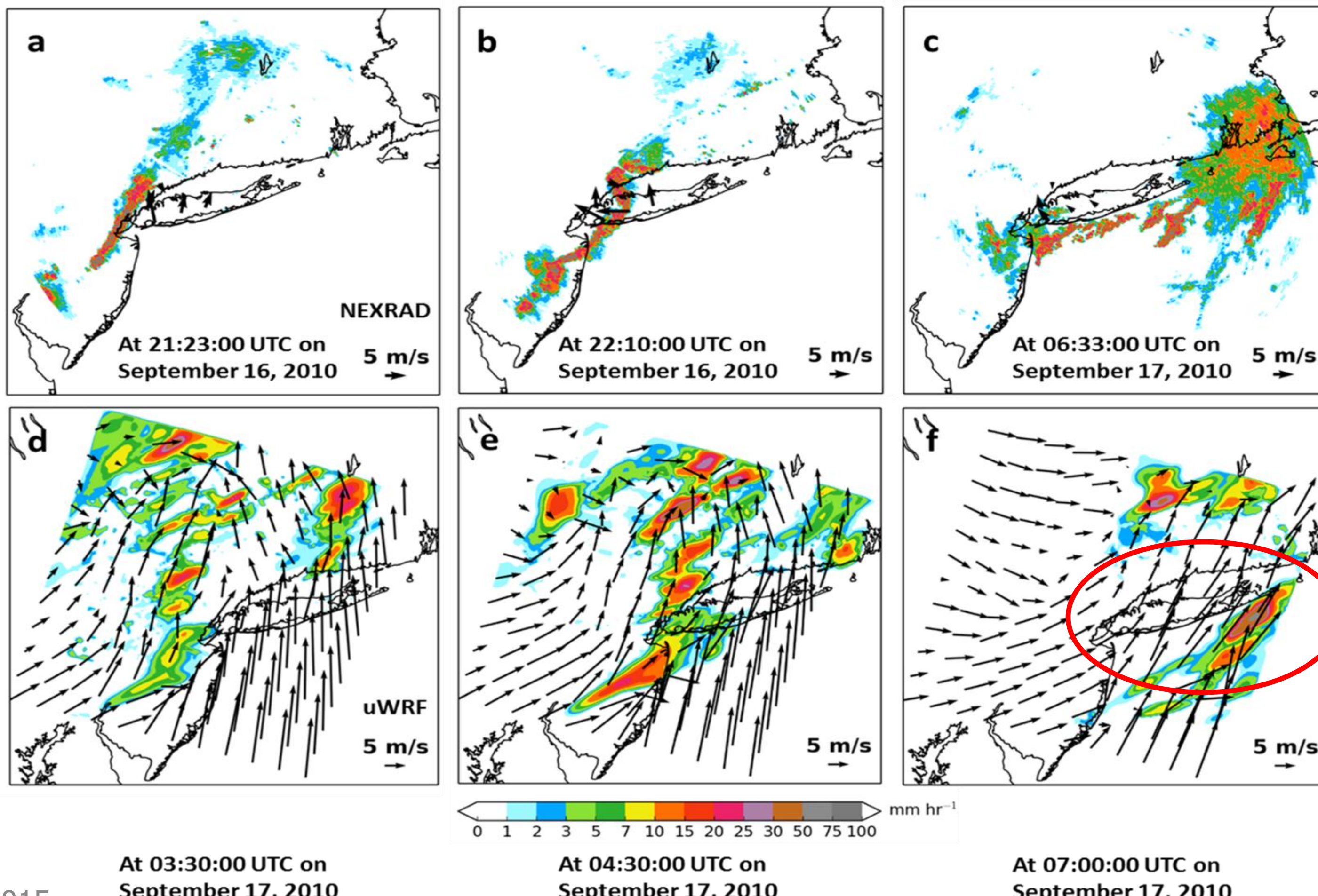


(u_1WRF minus no-city WRF) Precip-difference (mm)

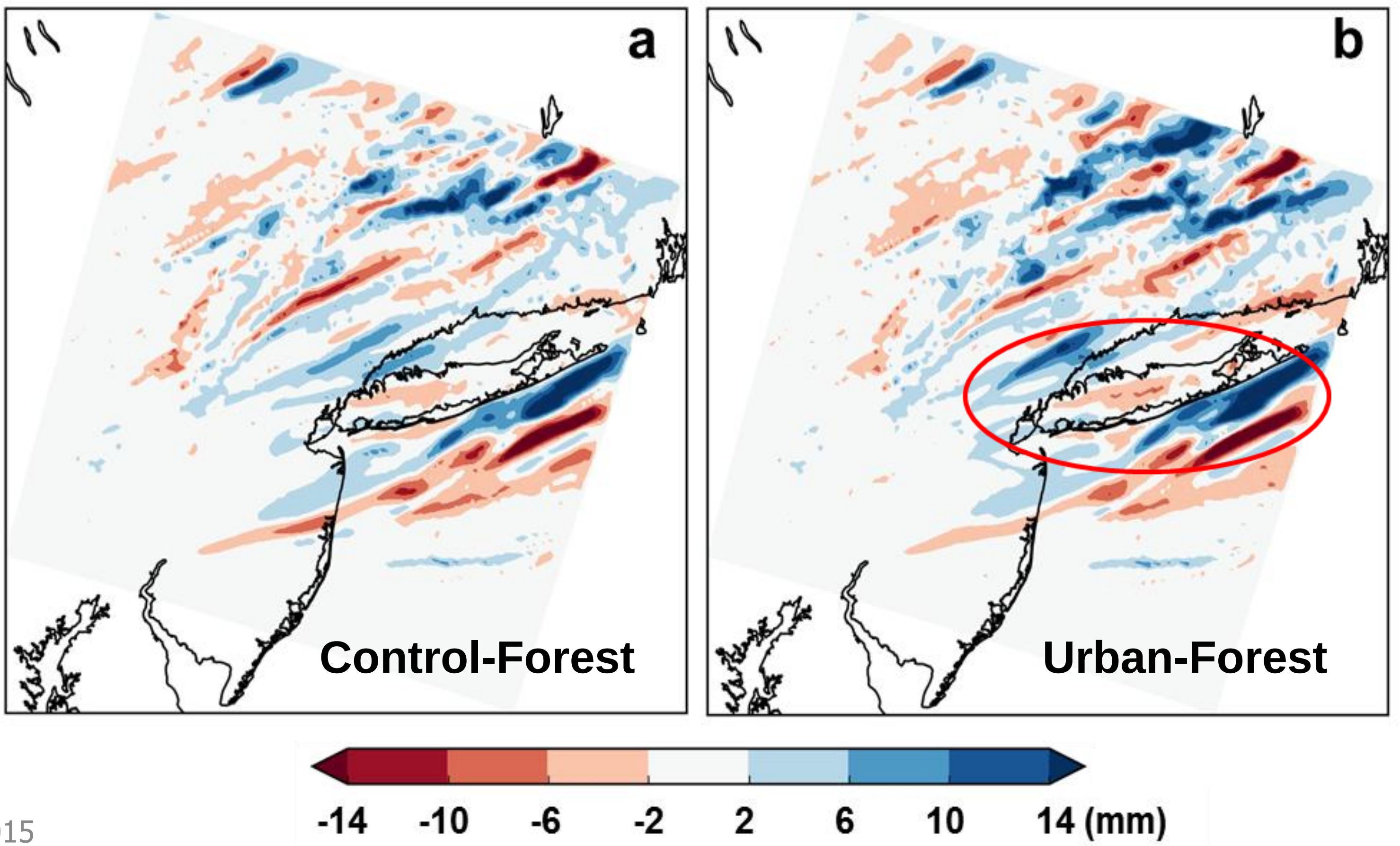
- **decreased** (green) in **inner city** (blue square) & **downstream**
- **increased** (yellow) in **surrounding** area west & SE of city
- this extremely-clear pattern seems to indicates subsequent additional (later than in previous slide) urban storm-bifurcation
- a golden case



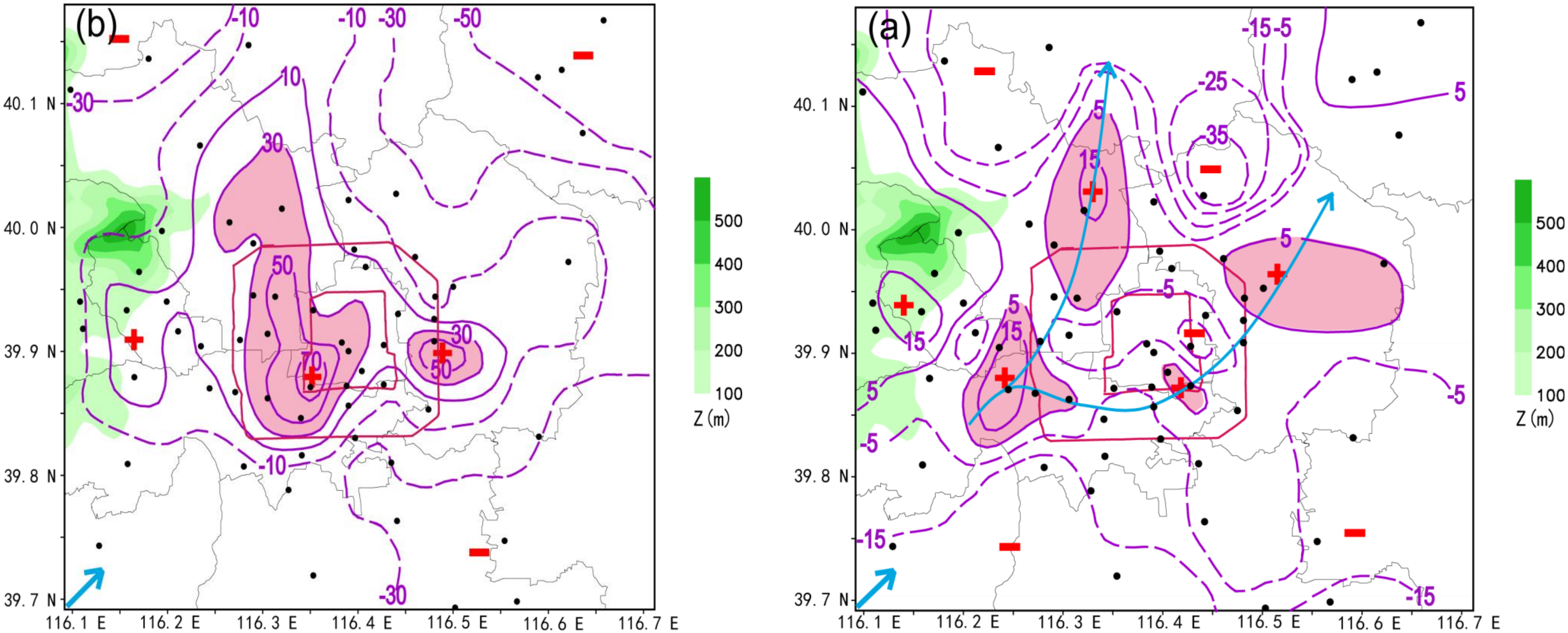
Study-2: NWS NexRad (a-c) vs. multi-level uWRF (d-f) echos, where uWRF has (a) 6-h delay in 9/16/10 storm-arrival at NYC & LI (E of NY, red circle) & (b) storm-bifurcation in uWRF (f), but not in obs (c)? Precip: next slide. By Wu, Ortiz, Gonzalez, Bornstein, Schooner, and Tongue (2015); Mon-Tues poster



> Differences (A-B) in total accumulated precip from 3 simulations: Control (WRF), Urban (uWRF), & Forest (replaces NYC)
> Note (b) shows larger urban-induced negative-differences (in red) over NYC & LI, surrounded by increases (in blue), i.e., storm bifurcation?   > What causes the ”distant” waves?



Syntheses slide (again), but now you know how we got here

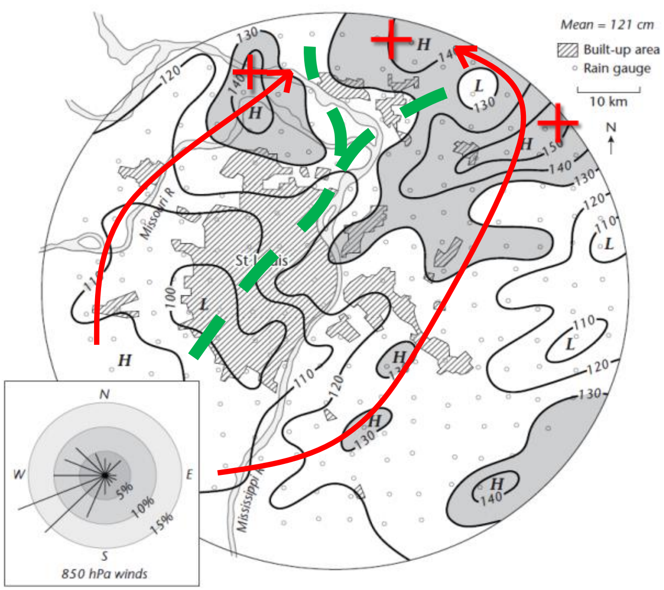


Beijing IUM climo-precip study (red circles = ring highway roads)

- Data: Normalized (by regional-average) 2008-12 summer-total rainfall-amounts N(%) only for 850 hPa SW-wind cases (blue arrow) *for*
- *(left) UHI (≥ 1.25 ℃, 79 cases) → UHI storm-initiation → urban max*
- *vs. (right) no UHI (<1.25 ℃, 55 cases) → barrier storm-splitting → urban min*
- *1st test of Bornstein (2011) hypothesis with UHI-data*
- *Dou (her MS), Wang, Bornstein, and Miao (2015) JAMC*

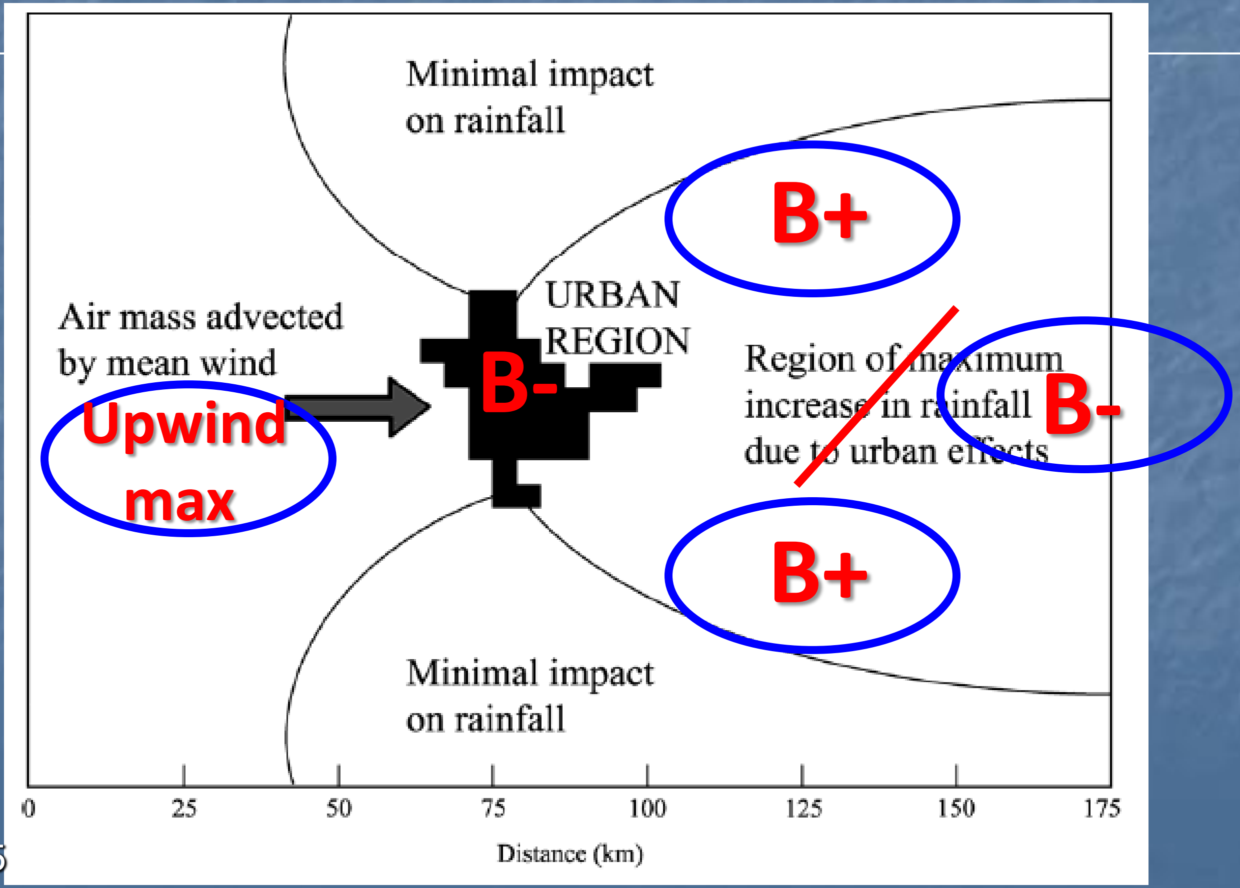
Can we reconcile METROMEX with Dou et al. (2015)?

- This analysis is from Semonin (1981), as reproduced by Oke et al. (2015)
- It shows only about 50% of the cases in the fig are from the SW
- But it is not segmented by UHI-mag, wind-direction, or day-night
- (All?) previous authors said it (& METROMEX, in general) shows only a downwind urban-max, but they did not cite the above limitations
- Even with these limitations, a rain-shadow-min (dash green line) & bifurcated lateral-max (+'s) are starting to appear. They should grow larger & clearer with the above segmentations
- It is also a matter of perception, i.e., knowing Dou et al., makes it easier to see the emerging downwind-min.



Can we reconcile METROMEX with Dou et al.? (Part 2)

Note: (1) original "summary" figure is from Shepherd et al. (2002)
(2) modifications are ours, where B's are barrier-effects, &
(3) upwind max is original-undisturbed max
(4) modification thus only provides details to original "downwind max"
(3) UHI-initiation cases would show only a max over city



Conclusions from Shepherd & Mills (2011)

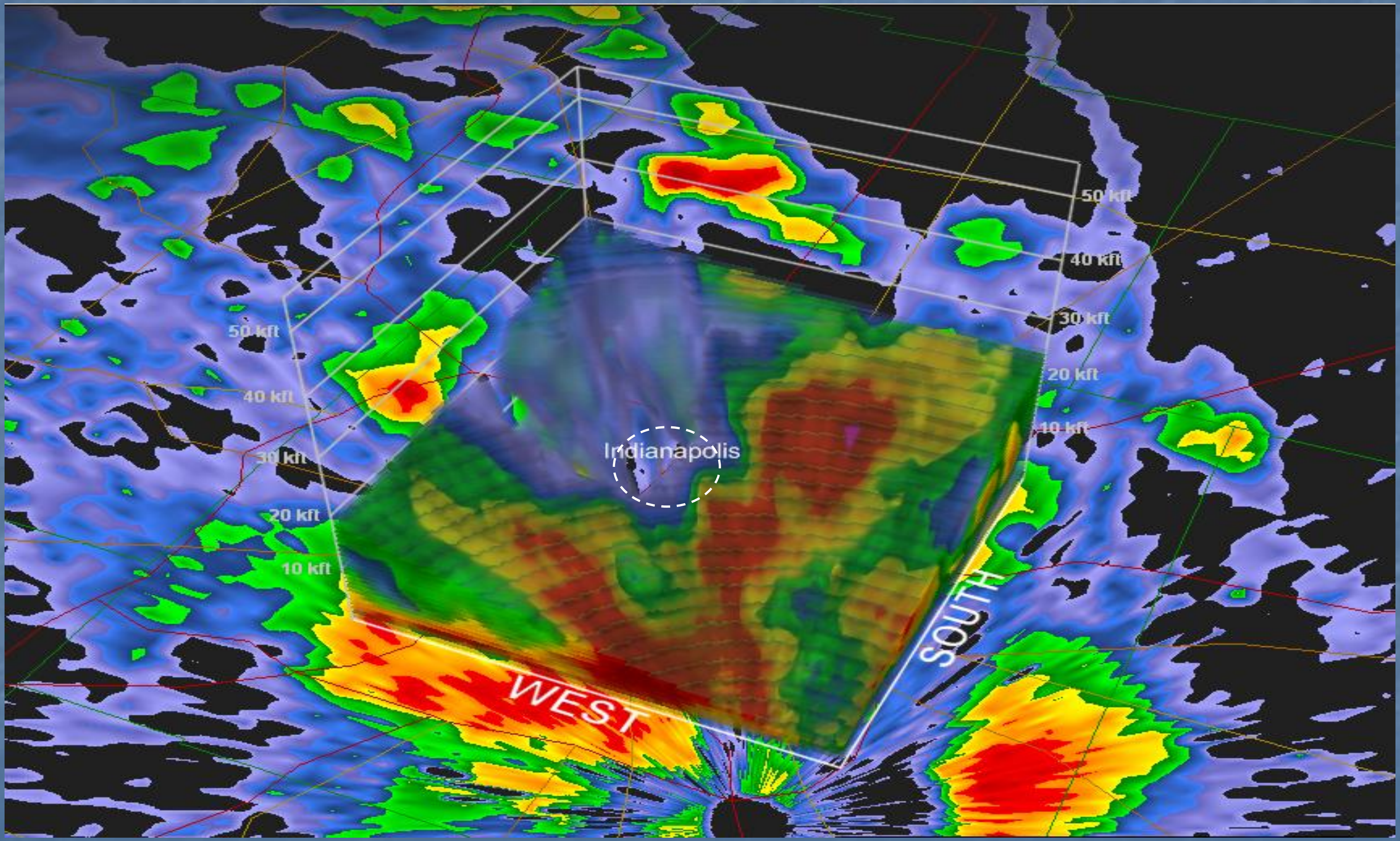
> Observing urban effects on precip: more difficult than examinations of temp, RH, wind, etc., due to both the nature of precip events & our observation systems

> Field resurged: as obs systems have improved & models can explore processes, but careful experiments are needed to detect urban effects

> Further developments in the field require (see following slides)

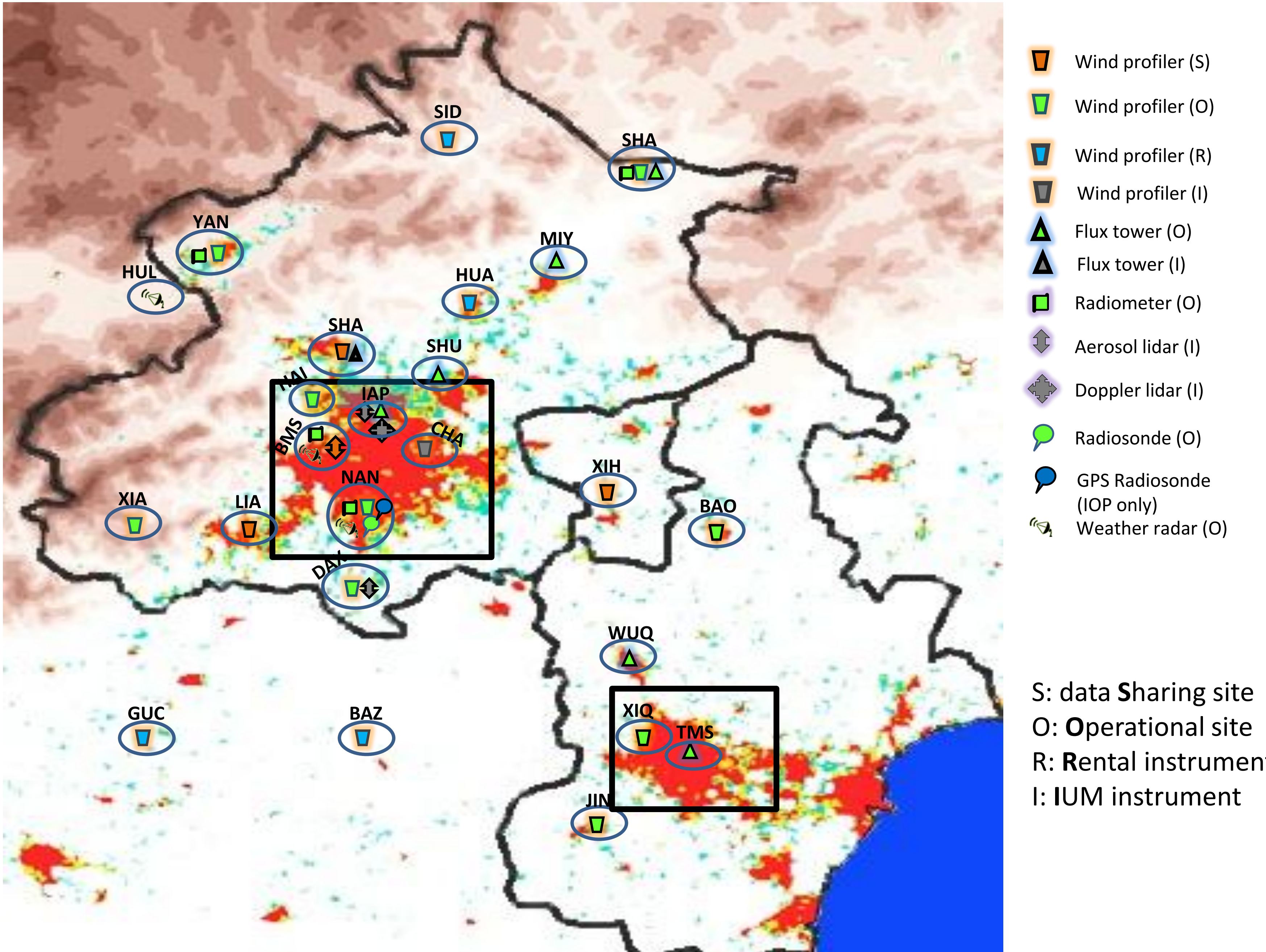
- New obs systems to track anthro & natural aerosols, land cover changes, cloud microphysics, and precip processes
- Long-term obs to detect precip trends from human activity (in-situ and remote sensing)
- Urban-canopy data for incorporation into new models
- Link science policy (planners) & operations (forecasters)

U.S. radar-image on 22 June 2012 at 1900 Z shows urban-induced storm-splitting



Summary of PBL-instrumentation (next slide) in ongoing 2015-7 IUM Beijing Field Study of Urban Rainfall-Impacts & Fog/Haze (SURF) program, with S. Miao as a lead scientist, & with an International Advisory Committee including, e.g., myself, S. Grimmond, W. Dabberdt, D. Niyogi, J. Gonzalez, F. Chen, et al.

	Operational (O)	IUM research (I)	Rental (R)	Data sharing (S)	Total
Wind profilers	9	1	4	2	16
Radiometers	4				4
Aerosol lidars		2		1	3
Doppler lidars		1			1
Flux towers	7				7
Weather radars	3				3



S: data **S**haring site
O: **O**perational site
R: **R**ental instrument
I: **I**UM instrument

Proposed model inter-comparisons: steps

- Form coordinating-committee
- Write guidelines: what cases could be simulated (e.g., they have a good urban-group, data, strong clear signal)
- Call for candidate "golden" cases of following types
  - UHI-initiated
  - barrier-split
  - no clear urban-impacts (e.g., noisy; or too-strong a storm, also can be of interest)
- Select first case
- Get data-set together & out to modelers (with their updated algorithms, e.g., hydrology, building energy, TKE)
- Collect, compare, & summarize results (at NCAR?)
- Prepare joint-publications
- Select next case

Some outstanding research issues

- How are winter storms effected by urban areas; Huff & Changnon (1986) addressed this issue.
- Why do storms bifurcate so far upwind of city, e.g., from a high pressure area and/or downward motions?
- How do urban surface-processes effect clouds with bases above the urban-PBL, e. g., vertical velocities?
- How do city "size," topography, storm strength, climate-type, etc., effect storm bifurcation?
- What is the relationship between sfc wind-direction & storm movement direction (what is storm-steering level)?
- If anticyclonic-shear causes storm-splitting over homogenous terrain, do urban areas cause such shears, and thus have more-freq storm splits/bifurcations, e.g., does urban frictional-retardation reduces the Coriolis, thus causing anticyclonic shear with-z?
- What is role of (a) deflections in bifurcation climatologies & (b) intensifications in initiation climatologies.
-

Influence of cities on clouds, precipitation, and thunderstorms

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Thanks! Questions??