Urban Impacts on Regional Rainfall Climatology

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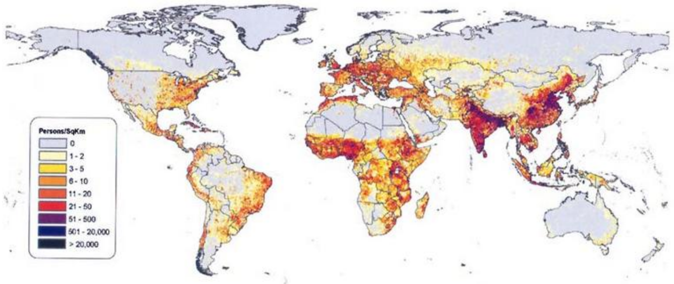
- \- What we know?
  \- What are we currently working on?
  \- Perspectives/ comments

- Acknowledgements - NSF CAREER, NSF STRONG CITIES, NASA ESSF, NSF AGS
- Yang Long, Paul Schmid, Daniel Aliaga, Ignacio De Garcia at Purdue
- Fei Chen, Marshall Shepherd, Bob Bornstein, Jorge Gonzalez, Jim Smith

What we know about Urbanization

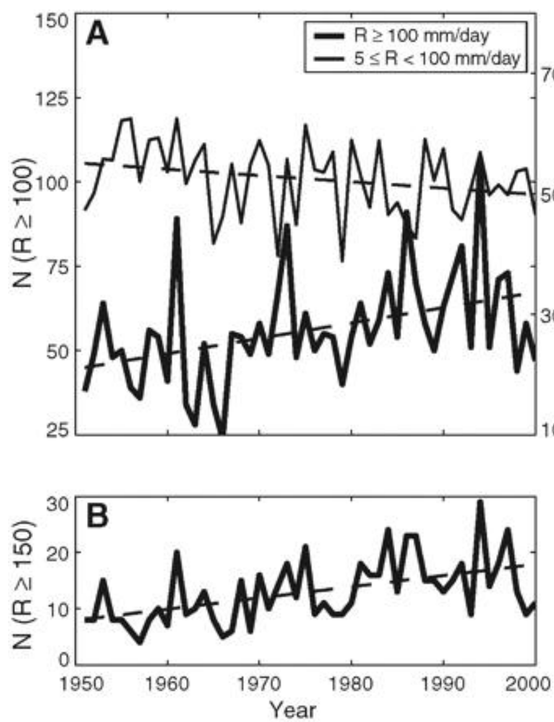
- New global change underway

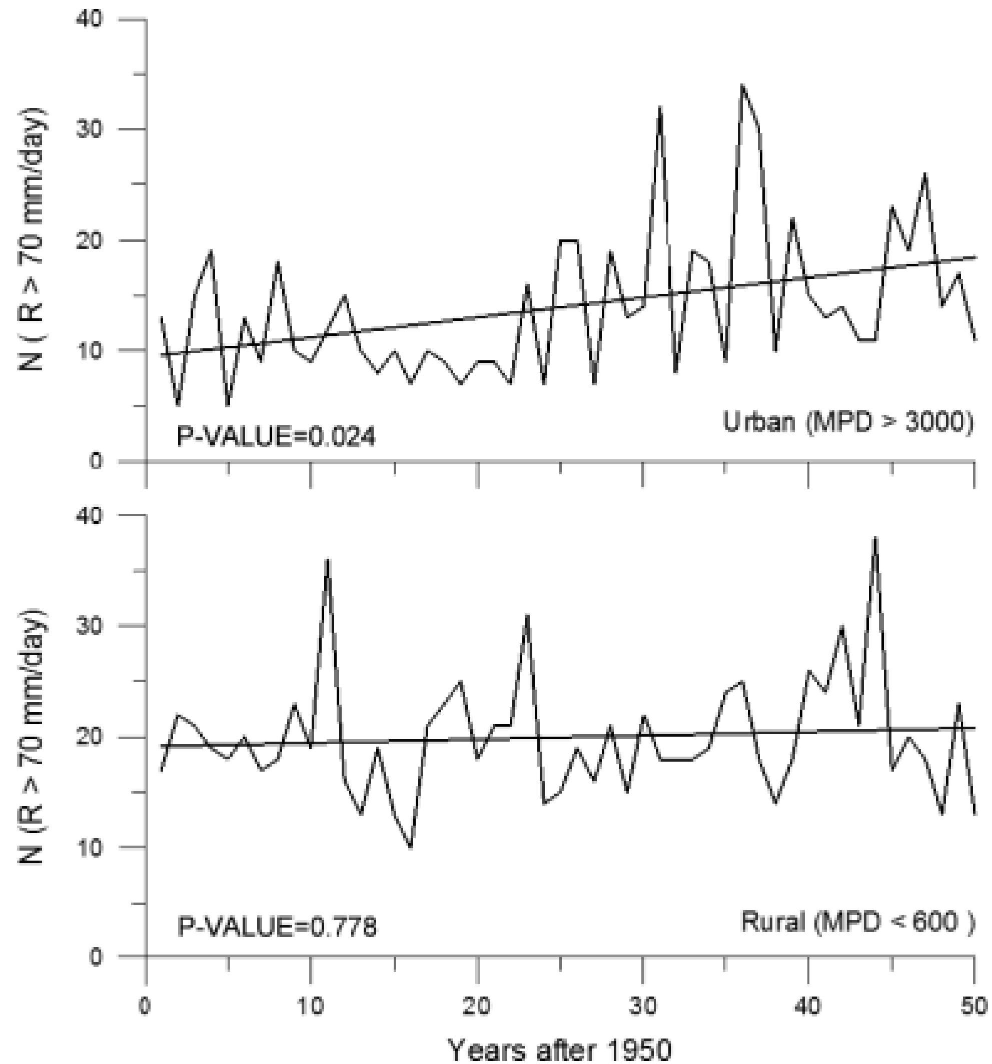


- **Causing significant, and detectable, changes in regional climate through temperature and rainfall modification (- no longer a hypothesis!)**

- UHI signatures at local scale (2- 10 C); and in climate data (about 0.5 C/ century i.e. about half the anthropogenic warming)
- Urban areas affect regional hydroclimatology in an even more profound manner than previous considered (affects heavy rainfall climatology)

Heavy rainfall trend over India (Goswami et al 2006 Science) only noted for urban grids (Kishtawal et al IJOC 2010)





Kishtawal et al. 2010, IJOC

Urbanization Impacts Scale Beyond the Surface Temperature

Urbanization → Temperature Change → Humidity Change (warmer air can "hold" more water/ higher saturation potential) /Surface Roughness Change

→change in available energy (function of T and q)

→ Bigger thermals / air circulation from surface to the atmosphere → Stronger convection potential

→stronger regional gradients

→Affect regional convergence/circulation

→Modify location / depth of cloud formation

→ Modify timing, location, intensity, duration of Rainfall

Urban Precipitation Modification (NRC summary)

Calm Conditions → Strong UHI → Convergence → Precip Maximum over Urban Center

Strong Regional winds → Upwind Divergence → Lateral/Downwind convergence → Precip Minimum over City. Lateral and Downwind Precip Maximum

Weak Regional winds → UHI → Convergence → Maximum Precip all advected to downwind urban edge

Urban Morphology and Size Significant to Spatio-Temporal Patterns of Convergence and Heating

After Formation
Aerosols Impact Precipitation Efficiency (x,y,t) and Lightning

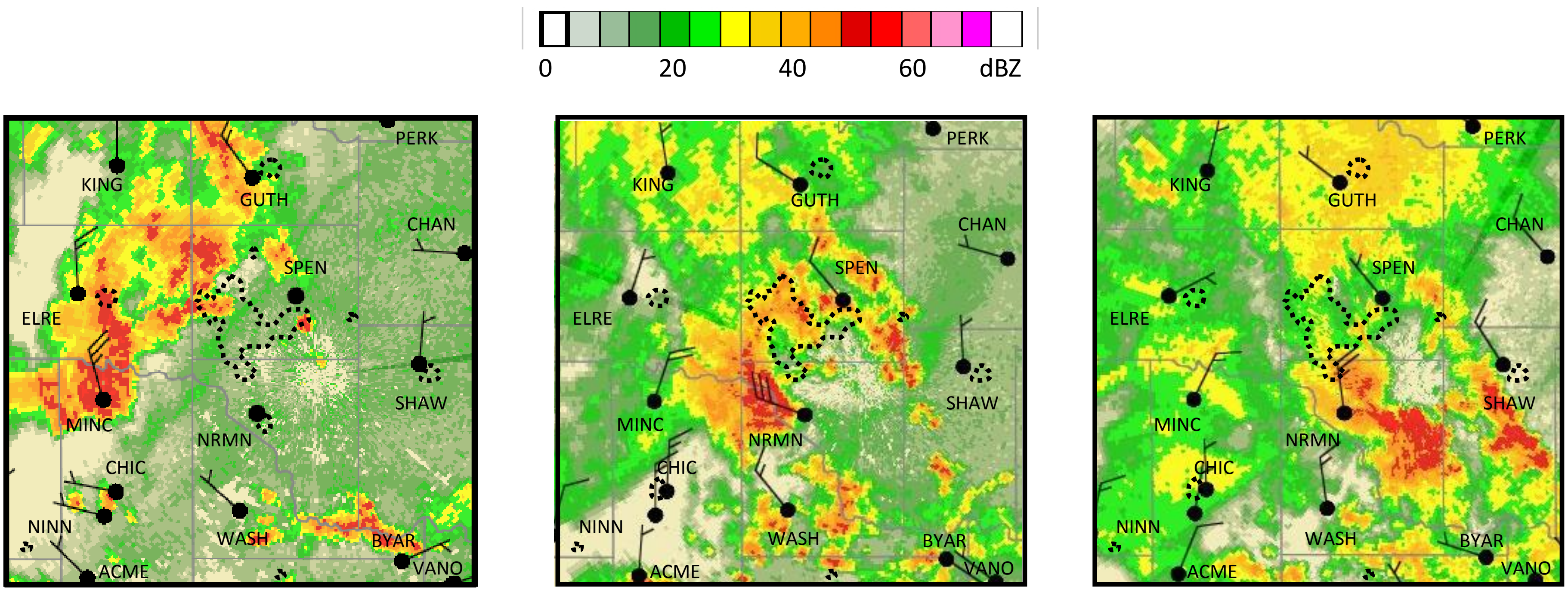
Other cross-cutting factors to consider:

Bifurcation-thermodynamic dome or physical barrier dome?

How does urban moisture and heat island affect local storm dynamics?

Seasonality? Diurnal effects? Topography?

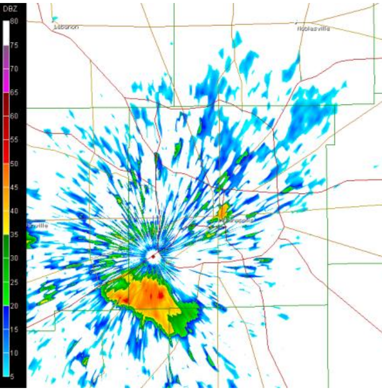
Example of Thunderstorms split/ intensify as they approach cities (Niyogi et al. 2006, JGR)



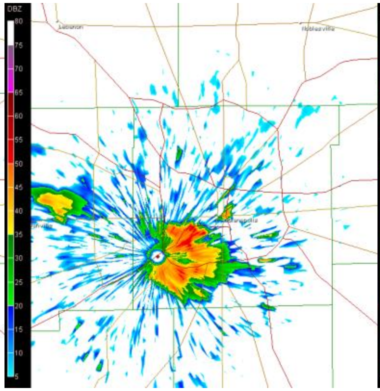
1015 UTC | 1100 UTC | 1130 UTC

Observed Base reflectivity (dBz) from OKC Radar representing nest 4 (1.33km) COAMPS simulation. Dashed figure represents OKC downtown urban area. Observed surface winds (full barb = 5 ms-1) are given by the OK mesonet stations.

June 13th, 2005 Radar Analysis
Individual storms show urban feedbacks



0002 UTC 14 June



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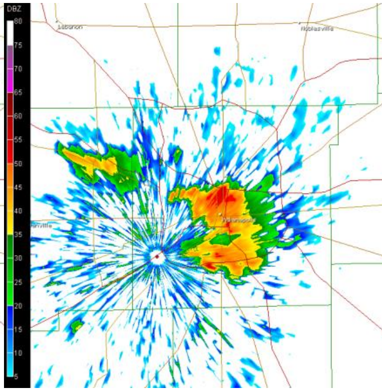

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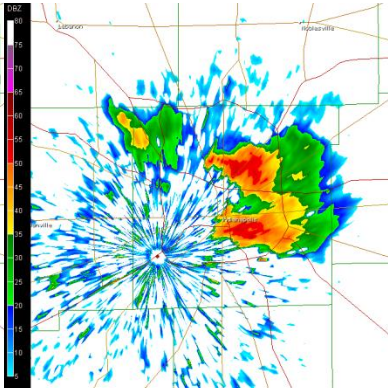

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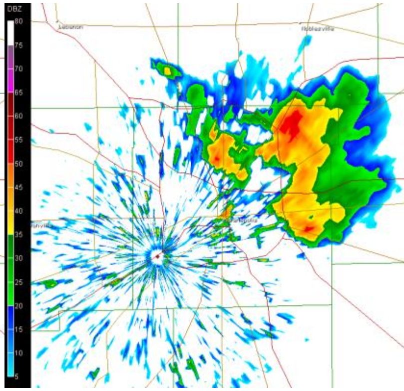

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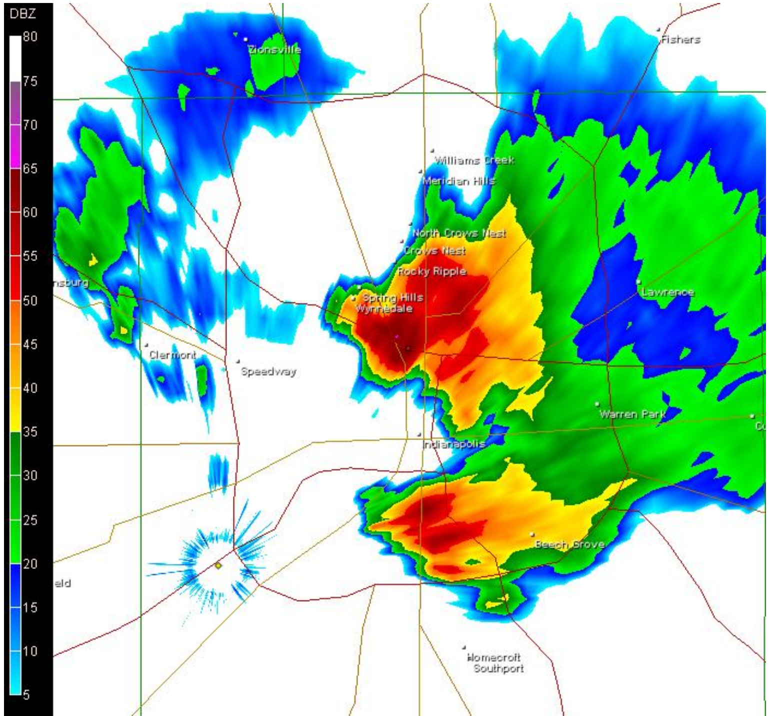
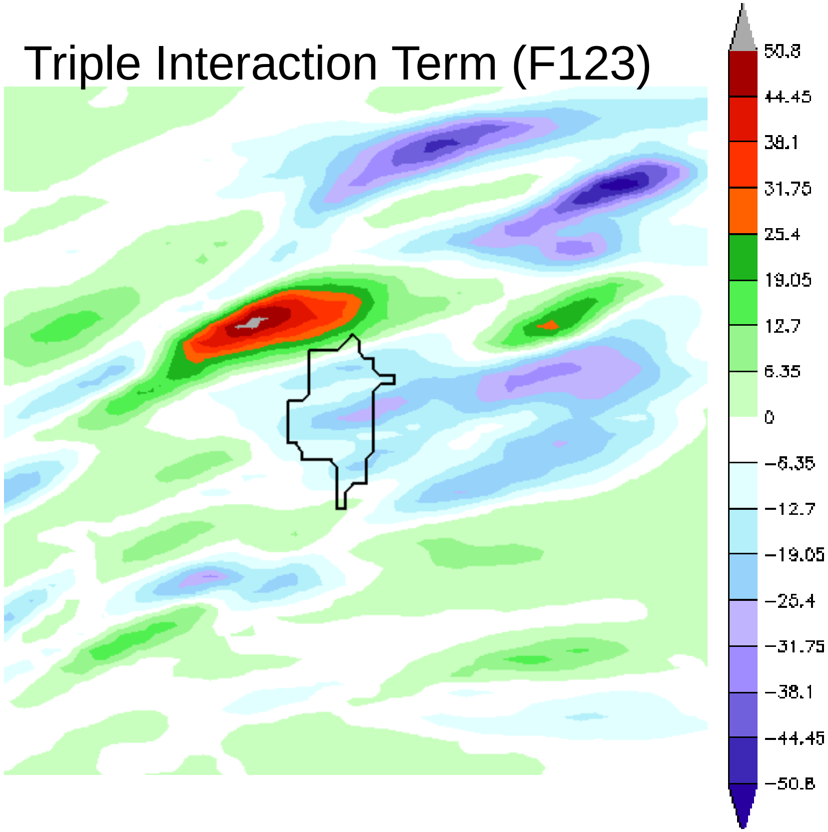


Why is there an urban feedback on rainfall? Not just urban but is a urban – rural heat flux gradients (convergence / divergence) based feedback

- Triple Combination of
  - Thermal Properties – (Albedo)
  - Surface Roughness – (z_0)
  - City size – (urban sprawl)
  - Create mesoscale convergence / divergence due to urban rural heterogeneities

Triple Interaction Term (F123)



Does every city affect every storm that passes over it?

(or when we have cities as a permanent feature, why some storms or studies do not show any modification / impact?)

- Majority (66+%) of the impact seen for day time slow moving storms, night time, fast moving storms show less impact
- First storm shows more impact, subsequent storms show lesser impact
- City size threshold needed (~ 25 km, Schmid and Niyogi, GRL)
- Not every storm will be split, or lead to more down wind rain (upwind enhancement is real; as is over city in some cases)
- Aerosols can interact with the dynamics and affect the location of convergence/divergence fields

- → Difficulty translated in attribution and assessment in some climatological studies that do not consider dynamics!

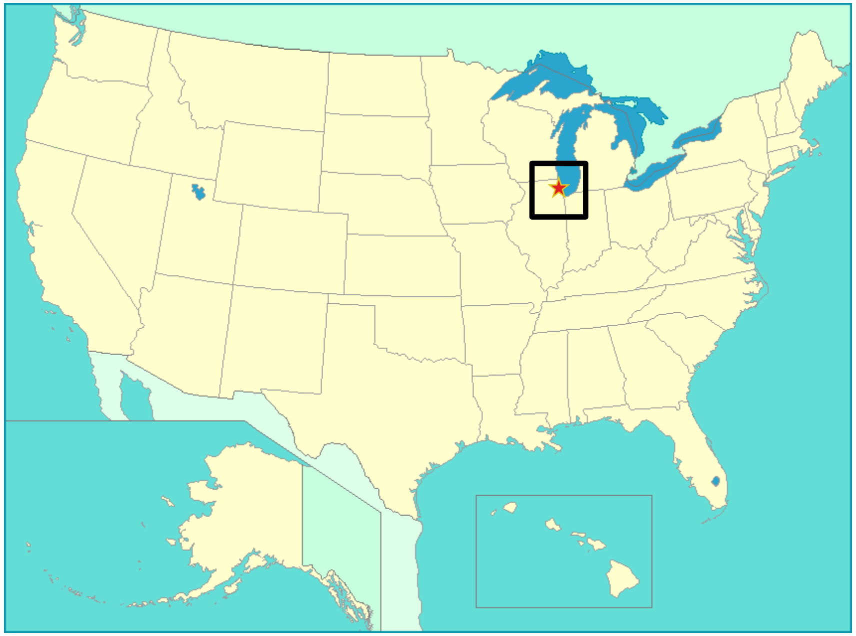
Elaborating the urban dynamics and aerosols perspective…

- Land surface interaction
  - Urban heat island forms due from heat retained by built environment.
  - Forces local updraft/downdraft couplets
  - Size of updrafts independent of city size. Larger cities have more updrafts.
  - Perturb storm inflow and updraft: rainout at city edge, delayed precipitation over city center.
- Aerosol interaction
  - Urban particulates (sulfates) act as CCN
  - Narrower, more uniformly small cloud droplet size: more smaller droplets
  - Suppresses warm rain
  - Invigorates cold convective rain
  - Deepens mixed phase
- Land surface is dominant. But aerosols are the variable saptiotemporal forcing.
  - Urban aerosol field often co-terminus with land surface.
  - We may be attributing aerosol effect: *enhanced convection due to cloud modification* to land-surface in some cases, and vice-versa.

- Upwind: aerosol boundary coterminus with land surface.
- Downwind: aerosols transported multiple times of city footprint (100km+).
- Scale of city
  - Land surface perturbations require more time to modify
  - Aerosols theoretically within minutes
- Aerosols lofted out of boundary layer by land surface effects.
- Once storm rains
  - Washes aerosol back to surface
  - Reduces effectiveness of heat island

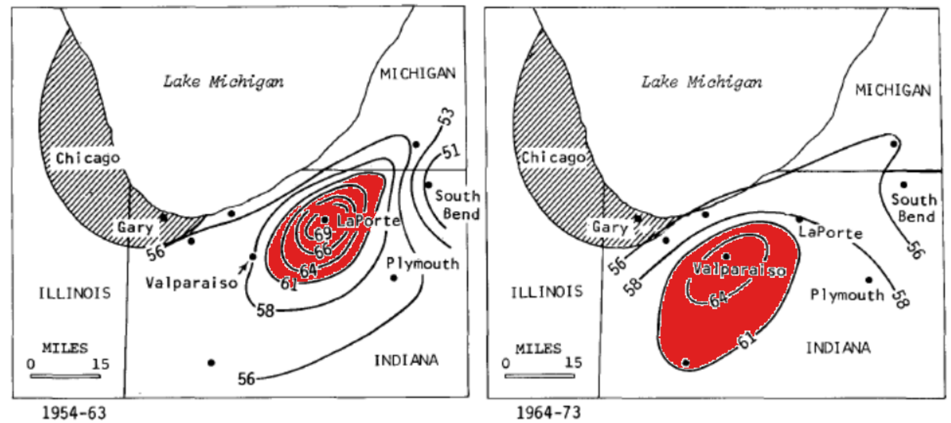
Updated History of the LaPorte Anomaly

Chicago Urban Area

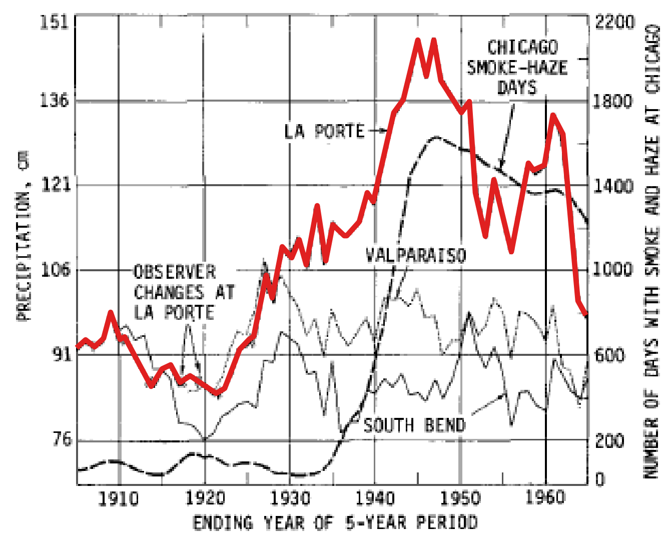


LaPorte, 1968: The Original Urban Rainfall Anomaly

- Changnon described anomaly in 1968.
  - LaPorte rainfall 30-40% higher than upwind in Chicago.
  - 20-25% more heavy rain days.
  - Later (1977, 1980) noted peak rainfall had moved westward.
- Debate over existence: Observer bias? “Ended” when automated rain gauge installed.
- Select articles
  - *The LaPorte Anomaly: Fact or Fiction*. (Changnon, 1968)
  - *The LaPorte Precipitation Fallacy.* (Holzman, 1971)
  - *The LaPorte Anomaly – Fact*. (Changnon, 1971)
- Led to METROMEX study in St. Louis metro area.



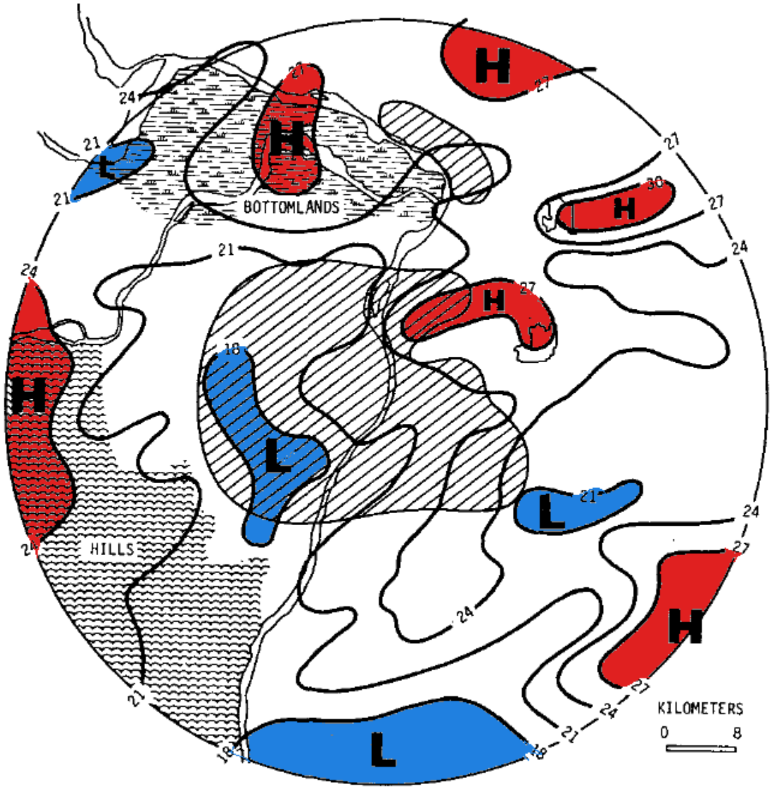
(Changnon & Huff, 1977)



(Changnon, 1973)

METROMEX: 1971-1975

- First organized study of urban convection.
  - St. Louis metro area
  - Characterize urban precipitation patterns
  - Provide hypotheses as to causes of anomalies
- Proposed mechanisms
  - *Combination of heat island and aerosol-cloud interaction.*
  - Heat island initiates storms
  - Splitting/merging due to airflow around city
  - Proposed giant CCN interaction.

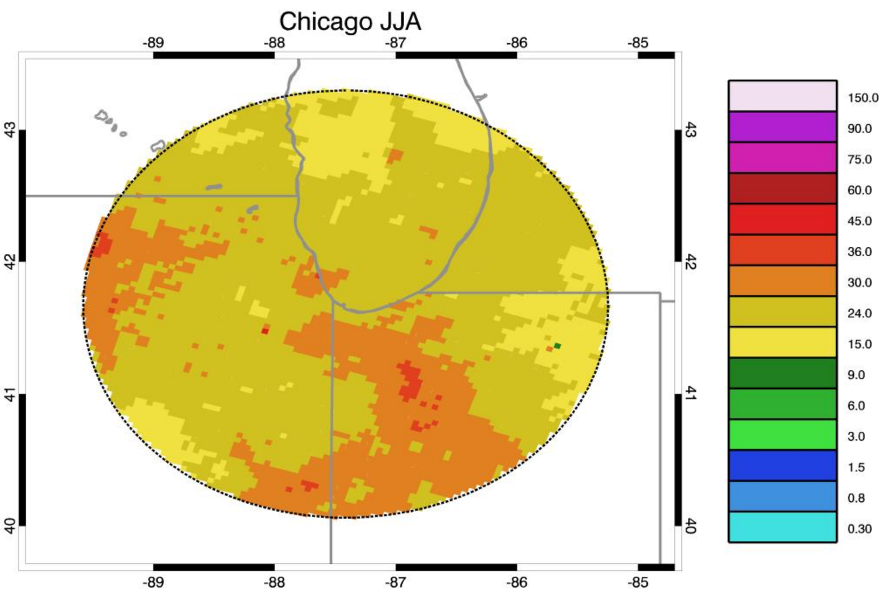


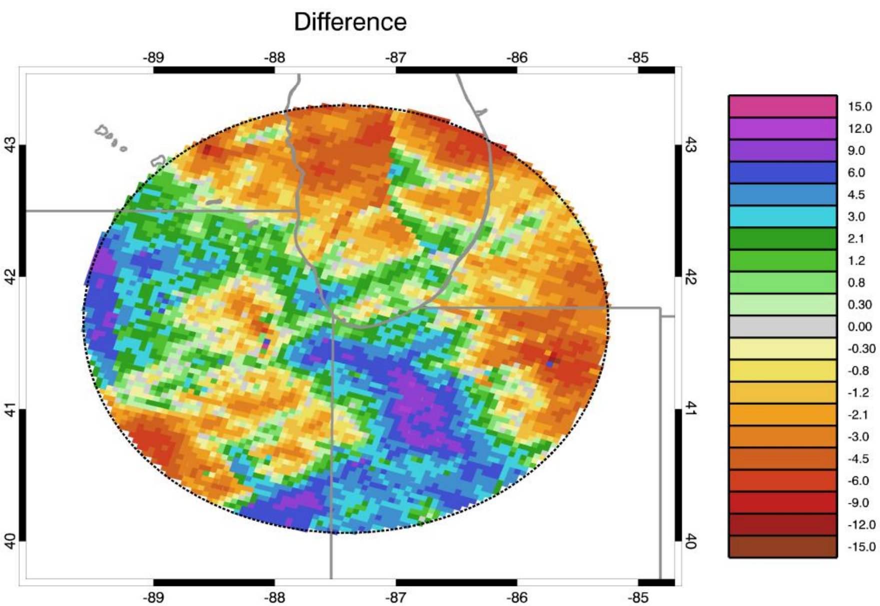
Changnon et al., 1976.

Challenges to Verify LaPorte

- Peak anomaly was not stationary: Moving westward when first described.
- Processes not yet described
  - Helped begin new land surface research.
  - Understanding of aerosol processes 30 years behind.
  - Remote sensing and modeling unavailable.
- Extent of anomaly *in part due to observer bias*.
- Seasonality bias?
  Winter precipitation enhanced by Lake Michigan, not Chicago.
- Last extensive original research on LaPorte published 1980.
- Contemporary research in urban weather based on theories proposed from LaPorte
  - Urban/rural boundary interaction
  - Urban heat island circulations
  - Aerosol cloud interaction
  - *Oldest theories, correct or not, still presented as most likely.*

Redid the whole analysis
Updated with radar datasets and improved dynamical/ aerosol considerations….."Final Word":
Yes, the anomaly exists.

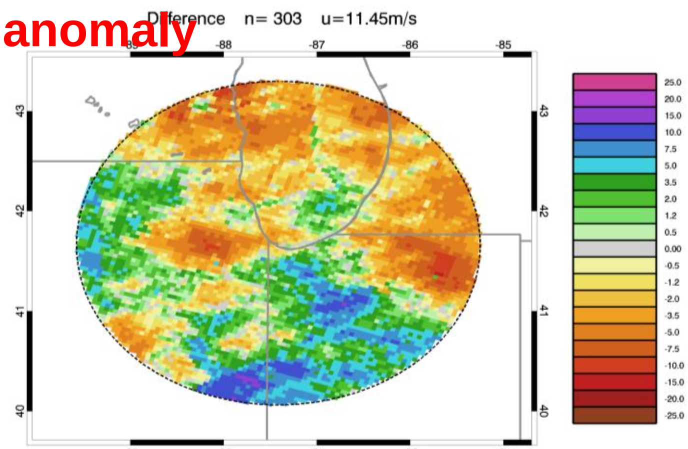




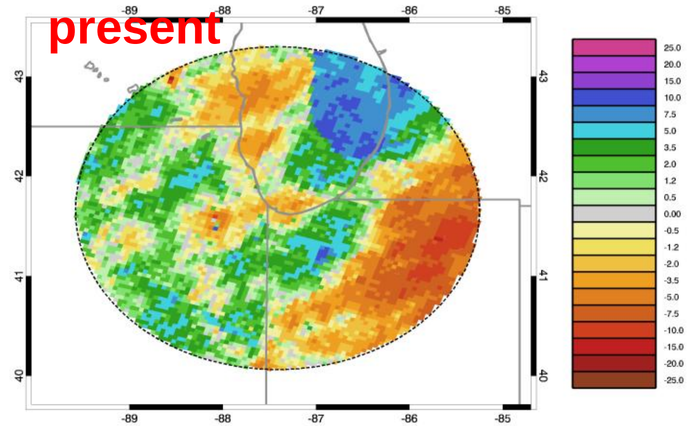
Ten year radar climatology (2005-2014) shows significant summertime rainfall anomaly, downwind of Chicago, peaking south of Valparaiso.

Chicago/ La Porte Observational Analysis

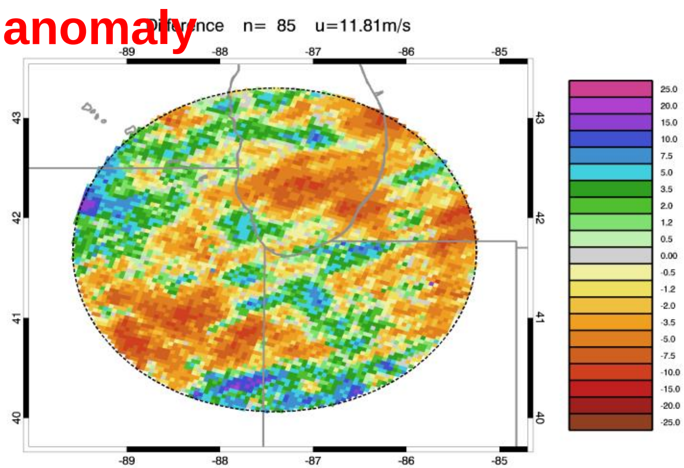
NW to SE moving → STRONG anomaly



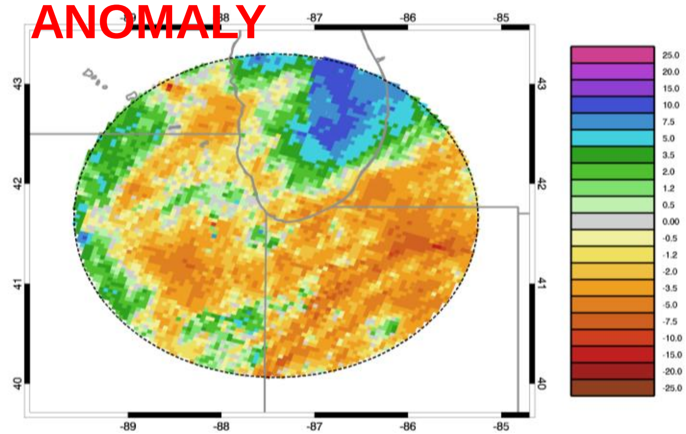
SW Wind Weekday → Anomaly present



W to E moving → weaker anomaly



SW Wind Weekend → NO ANOMALY



Looking for Urban Signatures beyond rainfall – effect on PBL height "climatology"

Evidence from High-Resolution Rawinsonde Observations

Objectives

The objectives of this study are twofold:

❑ Detect urban signatures from the perspective of PBL heights

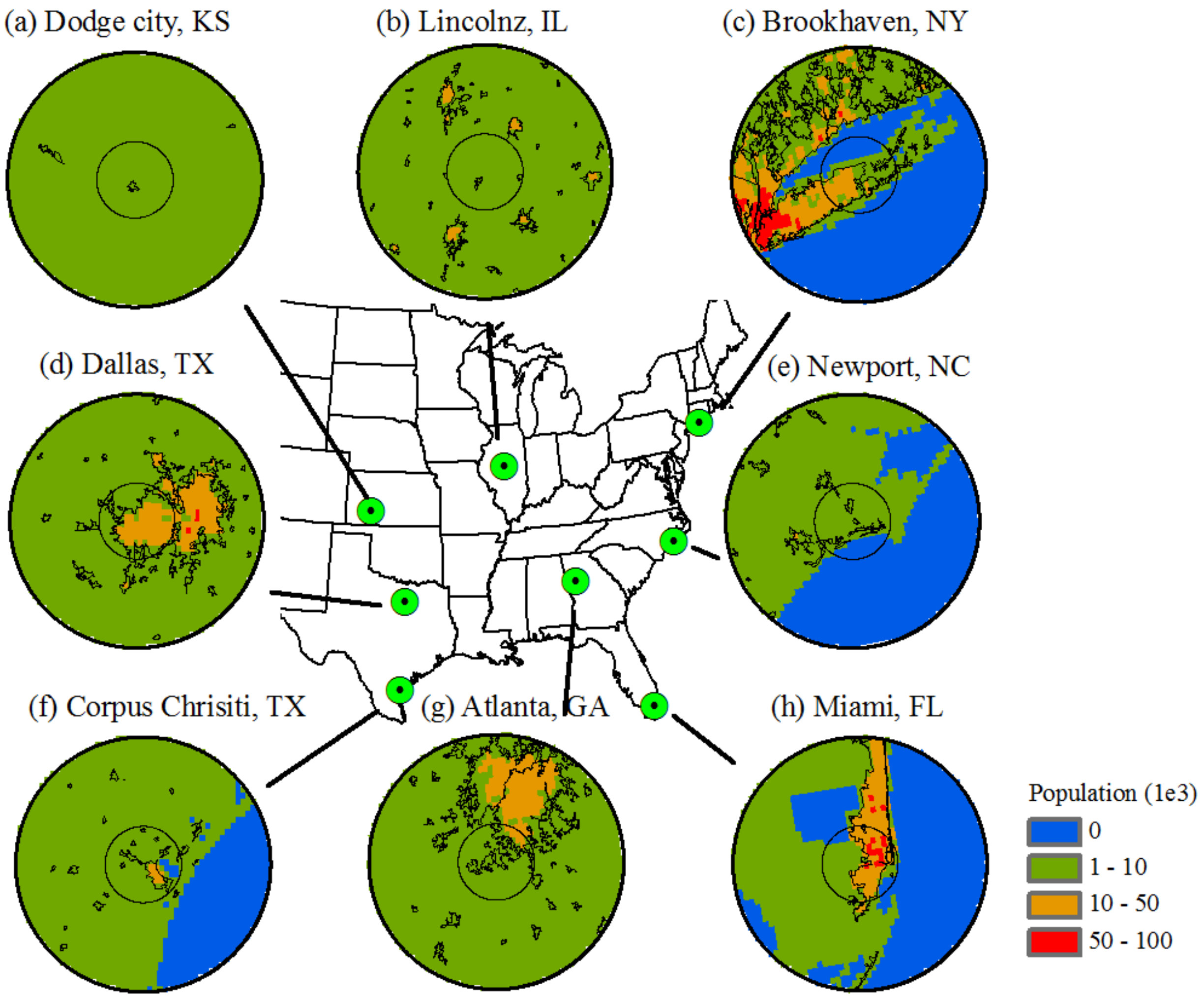
-Previous studies focus on urban heat island, urban rainfall enhancement and urban aerosols ;

-PBL height is a key parameter controlling land-atmosphere interactions;

❑ Derive climatology of PBL heights for representative US sites based on a high-resolution rawinsonde dataset

-Vertical resolution is a major source of uncertainty;

Selected Sites and sounding data



<u>Four categories:</u>

- ❑ Inland urban
- ❑ Inland rural
- ❑ Coastal urban
- ❑ Coastal rural

<u>Eight Sites:</u>

- ❑ 10-year sounding data with a vertical resolution about 30 m
- ❑ Twice daily (11 UTC and 23 UTC)
- ❑ Non-rainy day

Methods

I Bulk-Richardson number based method:

$$Ri = \frac{g\Delta\theta_v/\theta_v}{[(\Delta U)^2 + (\Delta V)^2]/\Delta Z}$$

Critical Richardson number is 0.25

II Statistics-based method (Schmid and Niyogi, 2012)

Basic theory: locate the top of the boundary layer by attempting to collocate a change in the slope of virtual potential temperature with a dew point inversion

$$\sigma(x) = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x}), \quad (1)$$

$$\kappa(x) = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left[\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2\right]^2} - 3. \quad (2)$$

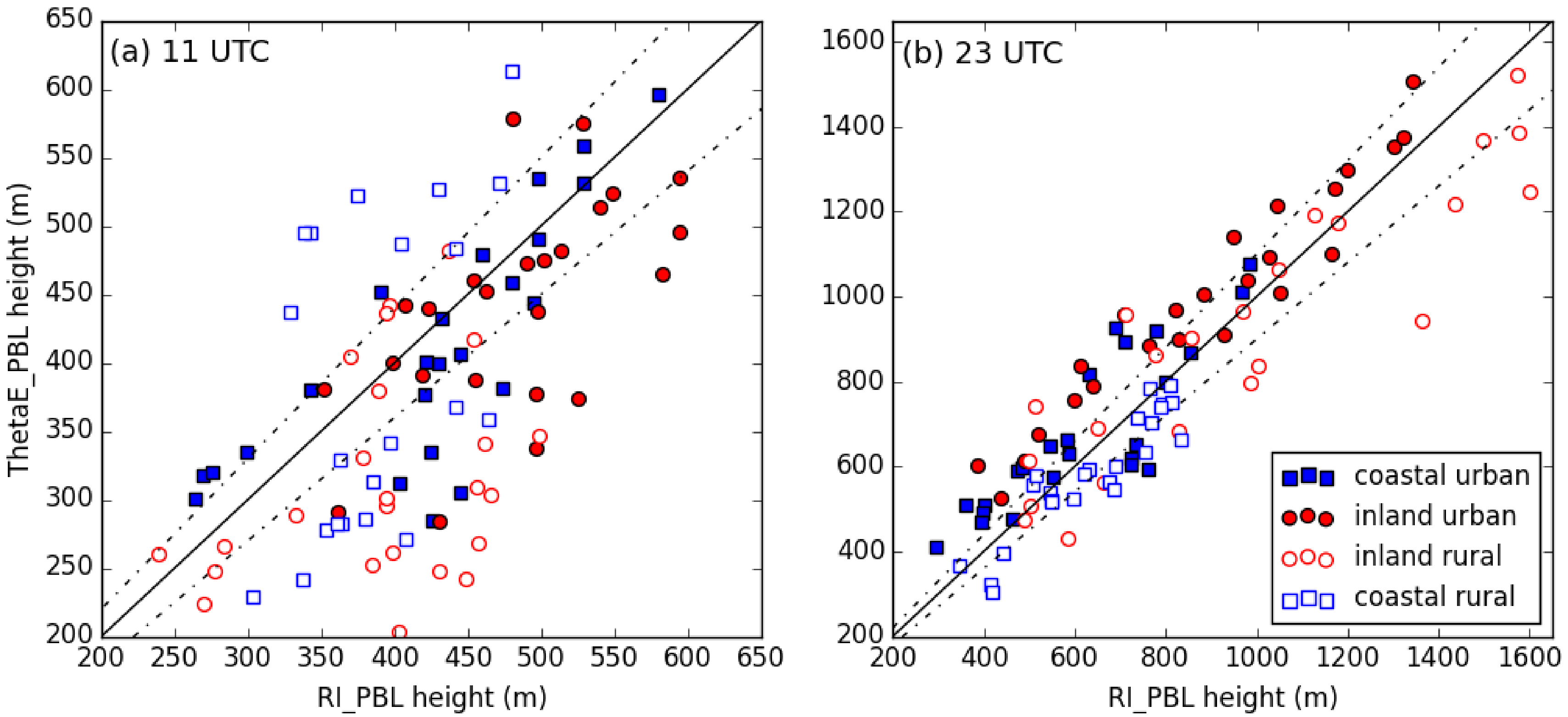
$$S_i = |(d_1 - d_2)\sigma(d_3)\kappa(d_3)|, \quad (3)$$

$$d_1 = \theta_v[(i-n):i] - T_d[(i-n):i], \quad (3a)$$

$$d_2 = \theta_v[i:(i+n)] - T_d[i:(i+n)], \quad (3b)$$

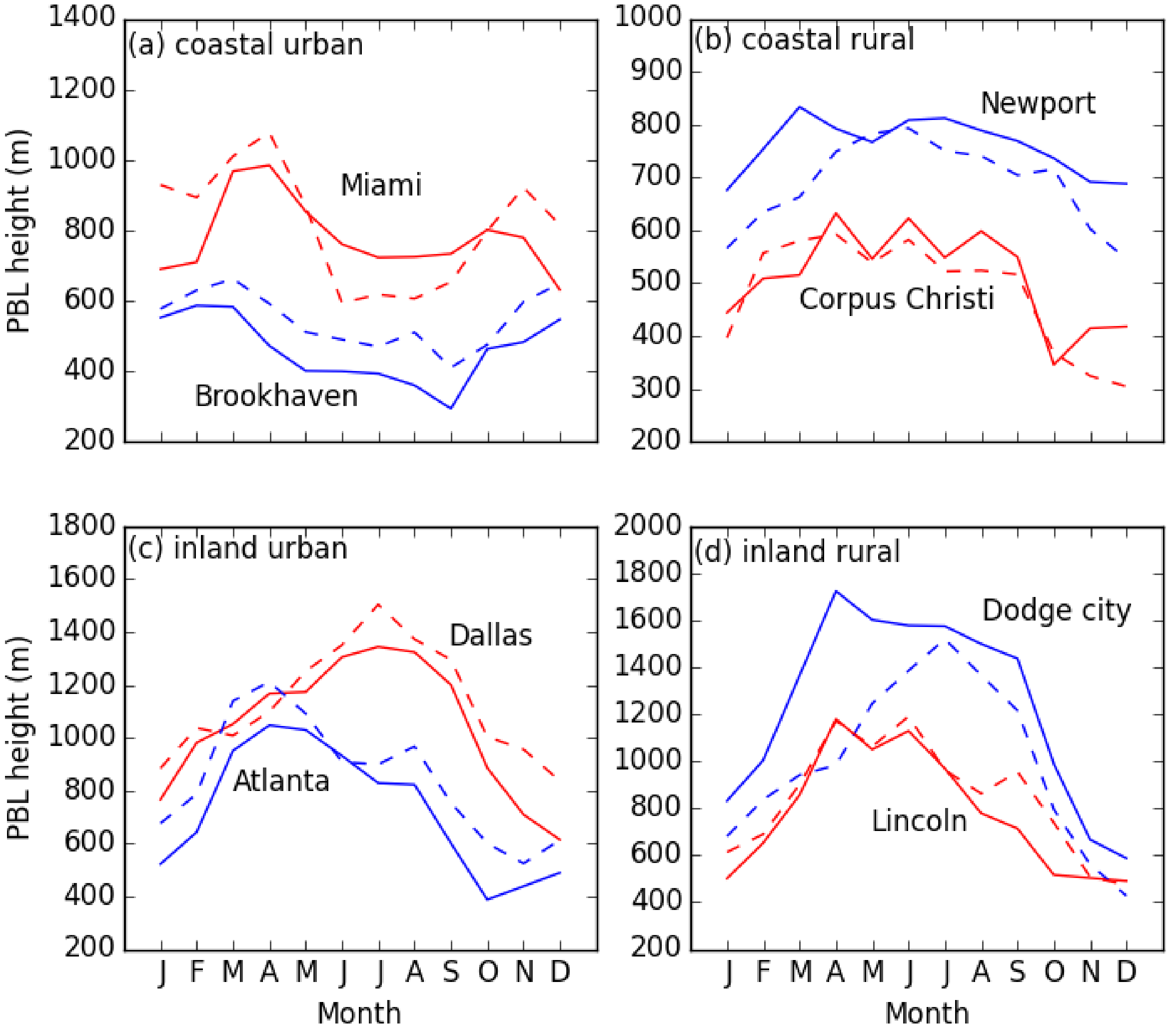
$$d_3 = \theta_v[(i-n):(i+n)] - T_d[(i-n):(i+n)]. \quad (3c)$$

Inter-comparison between two methods



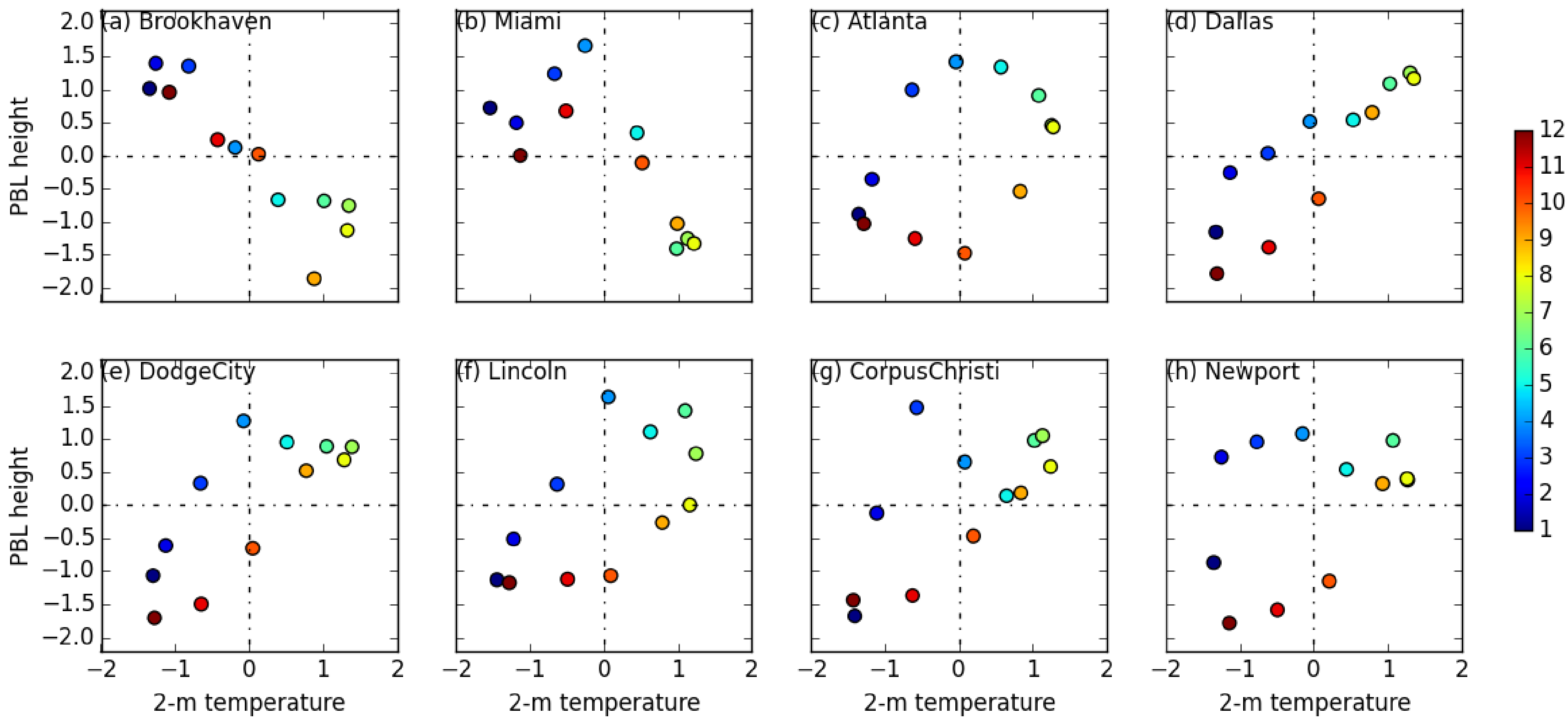
- Consistency for afternoon-time PBL heights;
- Richardson-number based method tend to underestimate morning-time PBL heights;
- Bias does not depend on land surface properties of sites;

Seasonality of PBL heights



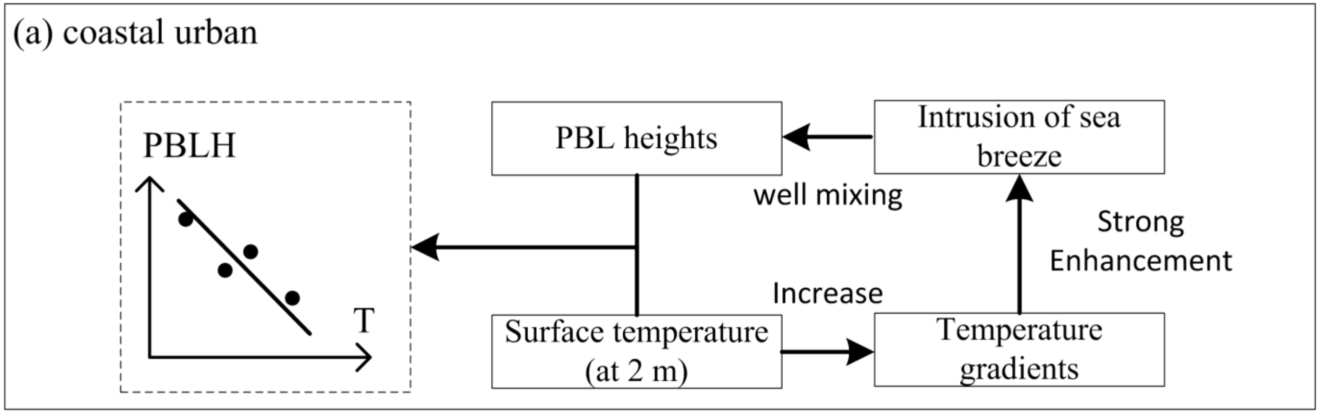
- Morning-time PBL heights do not vary much seasonally
- "unimodal" pattern for coastal rural, inland rural and inland urban sites;
- "bi-modal" pattern for coastal urban sites;
- Noticeably larger PBL heights for urban sites than rural sites;

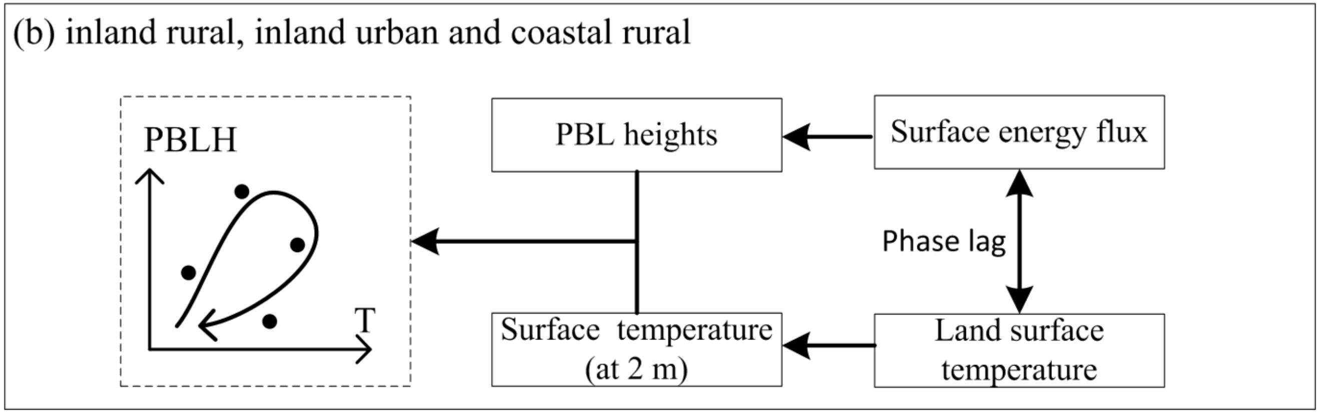
Seasonality of PBL heights



- ❑ Coastal urban sites: negative correlation with surface temperature
- ❑ Other sites: positive correlation with surface temperature and phase lag between two variables

Potential Mechanisms





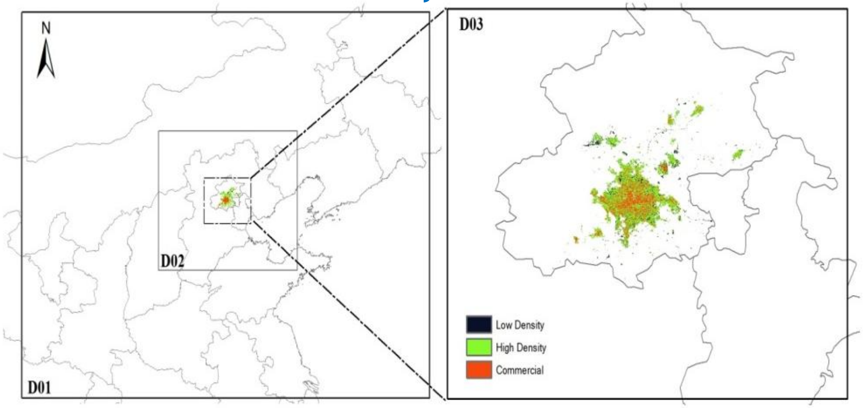
- ❑ **Coastal urban: land-ocean temperature gradients dominant**
- ❑ **Other sites: land surface properties (e.g., soil moisture) dominant**

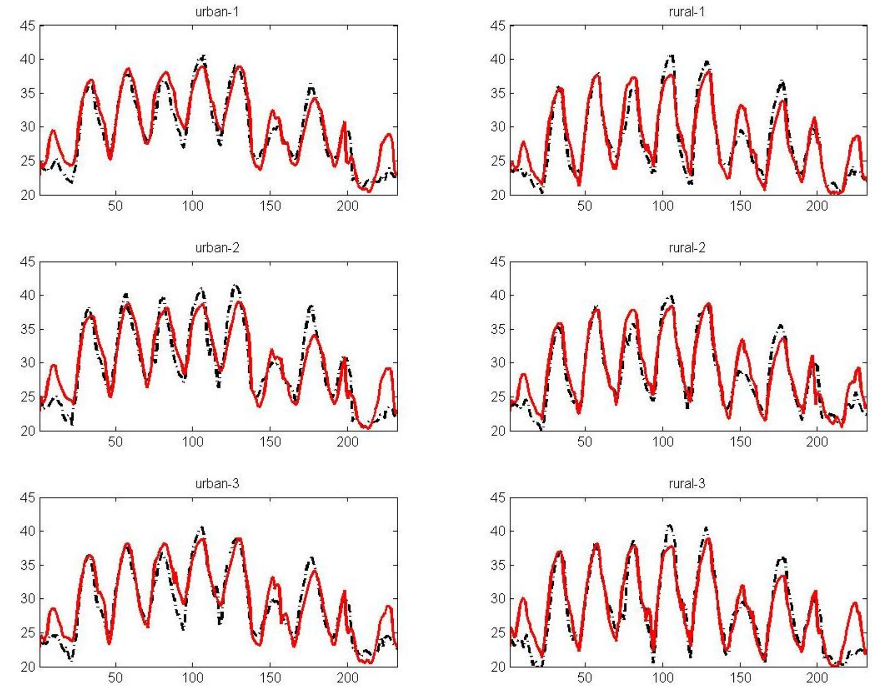
Impact of shape of city on regional climate

- Urban coverage is projected to be doubled over Beijing Metropolitan Area in 2050s;
- Different forms of urban development (compact vs. dispersed) could produce varied impacts on urban comfort and regional warming;
- We evaluate contrast thermal environment between two different ways of urban development under the context of climate change;
- We expect to provide suggestions to city planners for building future cities with more adaptability to climate change and heat-related risks;

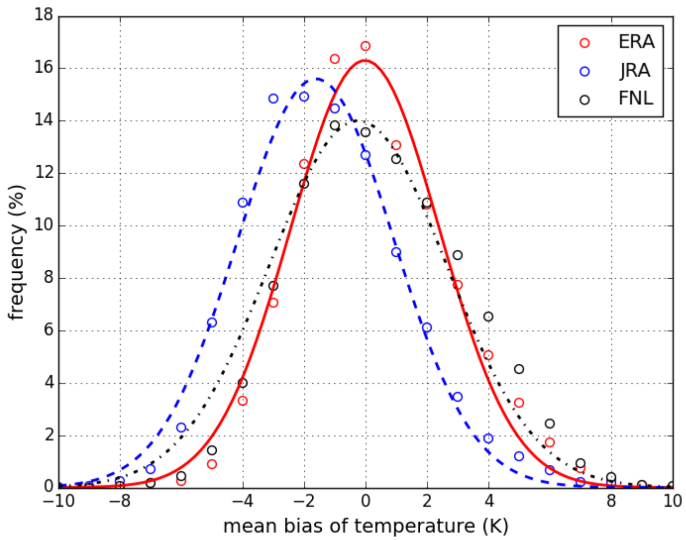
Model Configuration & Validation

Three One-way Nested domains





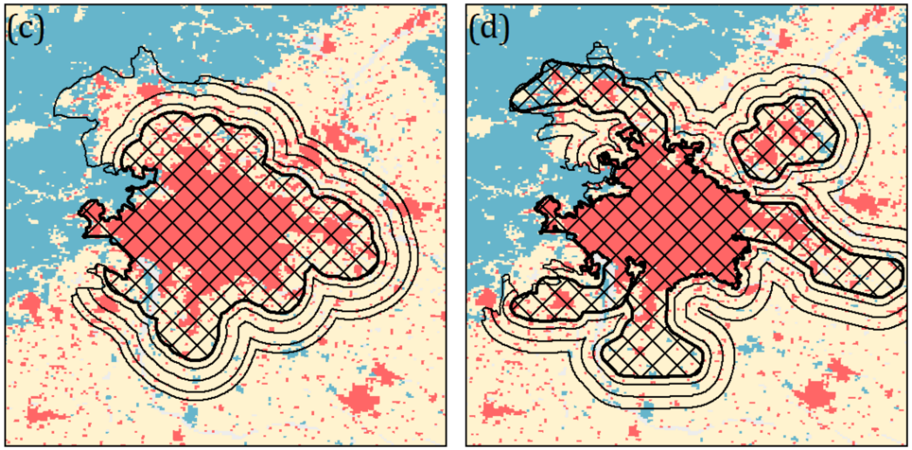
Distribution of Model Bias



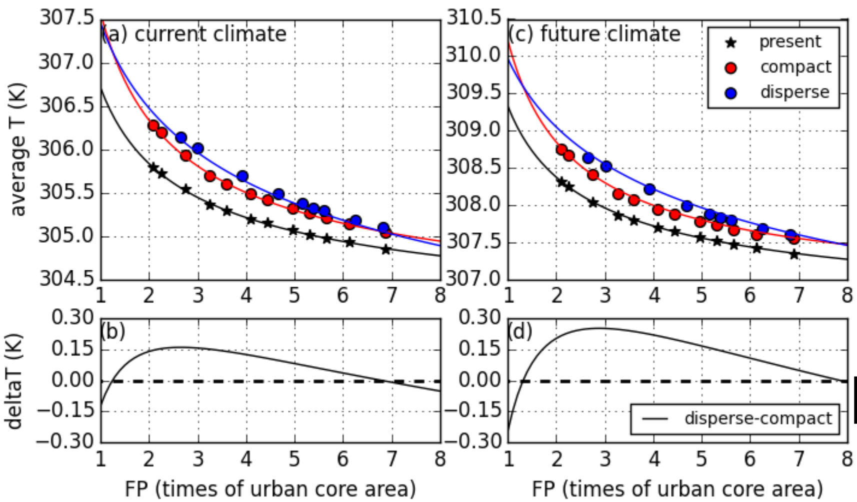
- ❑ Three dataset for Boundary/Initial Conditions: JRA-55, ERA-interim and FNL
- ❑ Simulated 2m temperature is not biased based on ERA-interim

Contrast Thermal Environment: Horizontal

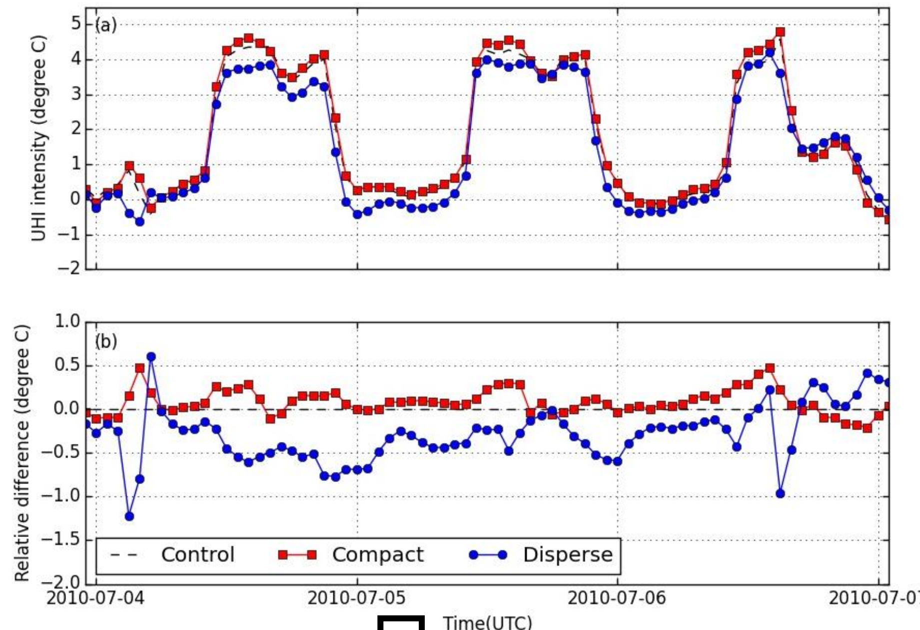
Compact-City VS Dispersed-City



Regional Warming Effect

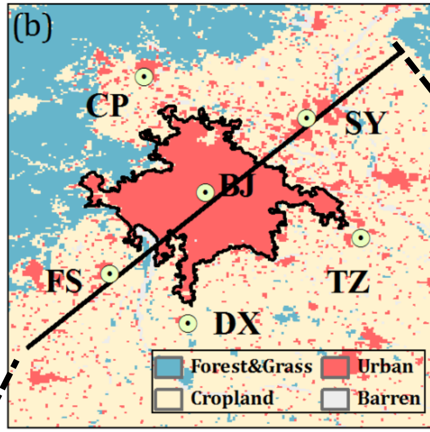


UHI intensity (UHII) = T_{urban} - T_{rural}



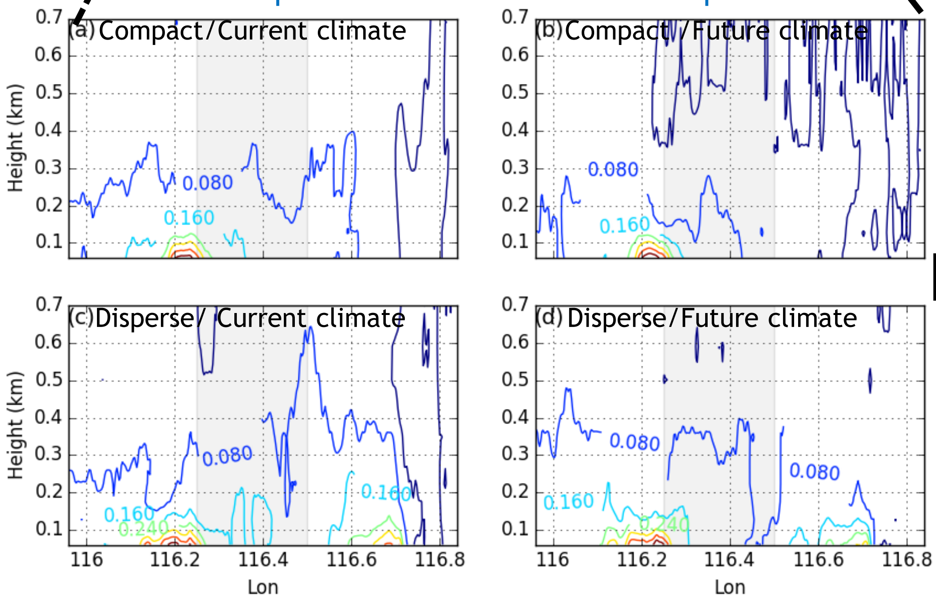
- ❑ UHII: Disperse < Compact, ~0.5 K
- ❑ Regional Warming:
  Disperse > Compact, ~0.1 K
- ❑ Urban warming:
  Disperse < Compact, ~0.15 K

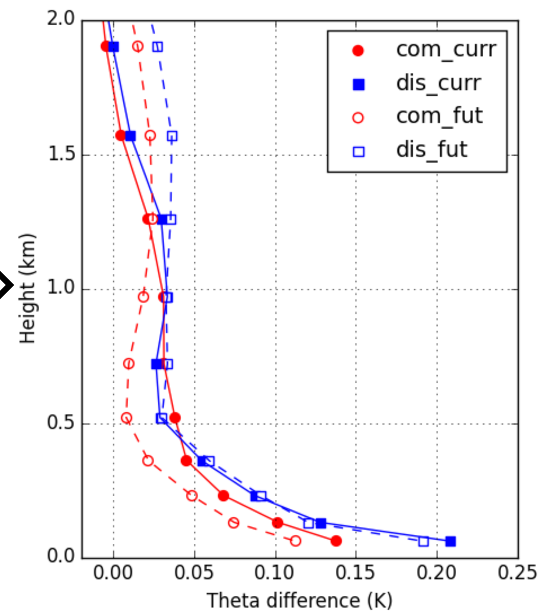
Contrast Thermal Environment: Vertical



- Dispersed-City scenario produce a relatively deeper perturbation on vertical profile of potential temperature;
- Implication for convective instability

Vertical perturbation on Potential temperature





Relative Contributions to regional warming

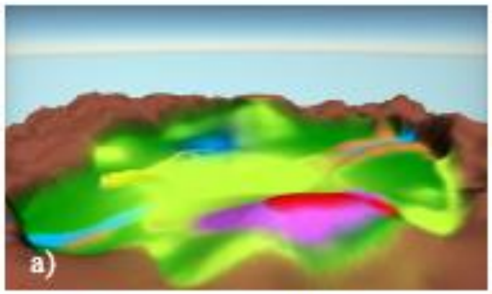
Scenarios	Compact-city	Dispersed-city
Total increase (K)	2.98	2.89
Due to Climate (K)	2.44 (82%)	2.44 (85%)
Due to Urbanization (K)	0.50 (17%)	0.40 (13%)
Interactions (K)	0.04 (1%)	0.07 (2%)

- ❑ Climate change contributes more than 80 % to total warming ;
- ❑ Different warming effect induced by spatial patterns of urban coverage is 0.1 K (~3% of total warming);
- ❑ City planners will need to weigh between regional warming and comfort in urban core region;
- ❑ Other mitigation tools (e.g., green roof) are needed to enhance urban adaptability to climate change;

Urban procedural modeling for high resolution modeling data input

Real-time Weather Simulation for Urban Procedural Modeling

Paper #0380



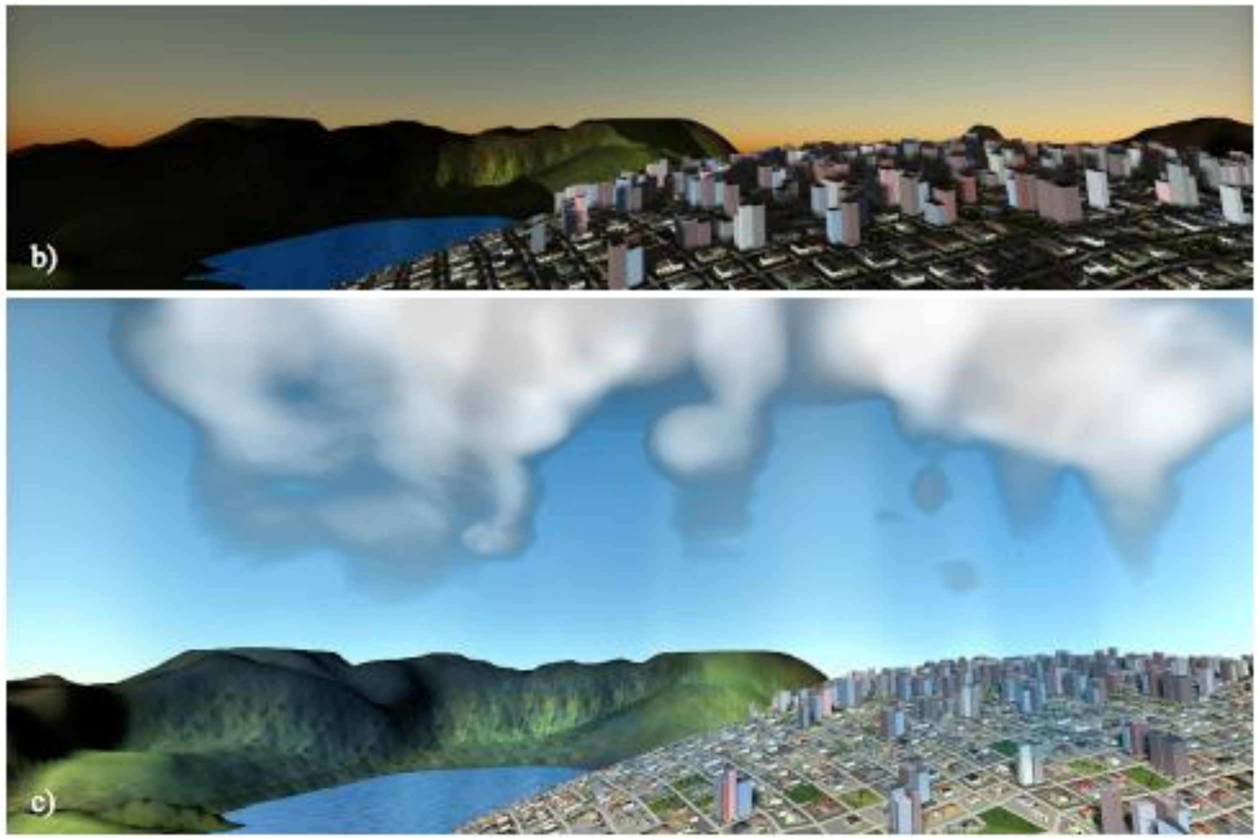


Figure 1. Urban Weather. *We present a method which tightly couples procedural modeling with a super real-time physically-based weather simulation. With our land use sketching interface (a), a user procedurally generates a terrain and city. Then, for example, our design tools enable intuitively choosing clear sky sunrise mornings (b) followed by afternoon showers (c) without providing details about realistic spatio-temporal behavior.*

a) Temp: 91.0F 0% Park, 0% White roofs

b) Temp: 89.0F 31% Park, 0% White roofs

c) Temp: 88.9F 0% Park, 61% White roof

d) Temp: 88.8F 17.7% Park, 48.4% White roof

Figure 13. Inverse-Based Design. *a) We show the original model; b) altered model that achieves 2 degree reduction by introducing more parks; c) alternative model that uses white roofs of increased albedo; and d) a solution with both parks and white roofs though less then when used individually.*

Simulation Technologies for the Realization of Next Generation Cities: Traffic/Weather Coupling and Urban Planning

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Purdue University

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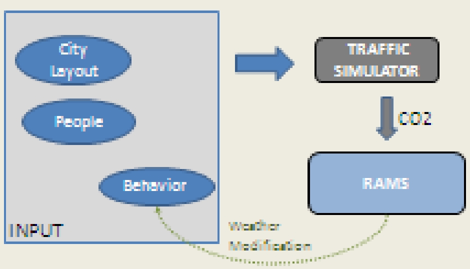
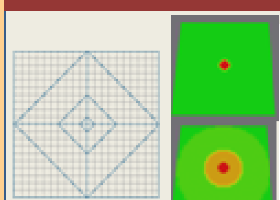
Introduction

- Cities modify their local climate in two ways
  1) Land surface heterogeneity.
  2) Aerosol-cloud interaction.
- Meteorologists have sophisticated weather models.
- Urban planners have sophisticated traffic models.
- As aerosols from traffic can modify the weather, the people creating the traffic will respond. This has not been modeled.
- To better understand the city – weather interplay, we need to couple *human behavior* with weather using computation/simulation technologies.



Urban Model

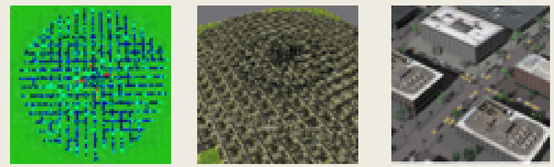


Local Climate Zone	[illegible]	[illegible]	[illegible]
Pop. Density (/km^2)	[illegible]	[illegible]	[illegible]
Job Density (/km^2)	[illegible]	[illegible]	[illegible]
Pop. Density (/km^2)	[illegible]	[illegible]	[illegible]
Job Density (/km^2)	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
Building Density	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
Canyon Aspect Ratio	[illegible]	[illegible]	[illegible]
Building Roughness	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
Roof Albedo	[illegible]	[illegible]	[illegible]
Roof Emissivity	[illegible]	[illegible]	[illegible]
Road Albedo	[illegible]	[illegible]	[illegible]
Road Emissivity	[illegible]	[illegible]	[illegible]
Wall Albedo	[illegible]	[illegible]	[illegible]
Wall Emissivity	[illegible]	[illegible]	[illegible]

- Idealized circular city with concentric districts.
- Three distinct urban land cover types to represent three districts of city.
- Based on simplified local climate zone paradigm (Stewart et al. 2012; Stewart 2012).

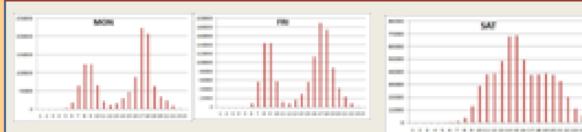
City Group	CBD	Old City	Suburbs
Radius	[illegible]	[illegible]	[illegible]
Size (km^2)	[illegible]	[illegible]	[illegible]
Size (km^2)	[illegible]	[illegible]	[illegible]
Population	[illegible]	[illegible]	[illegible]
Jobs	[illegible]	[illegible]	[illegible]

Traffic Generation



- Prescribe: Rush hours, percent of population commuting, and errands.
- Fast traffic microsimulation of 500,000 individual people (Garcia-Dorado et al. 2014; Aliaga et al. 2012):
  - Home and job distribution → Start and end point.
  - Individual routes → Iterative process to find traffic equilibrium.
  - Simulation → Lane changing and car following model.
  - CO_2 emission calculate per car for each time step simulation (0.5sec).

Traffic Results

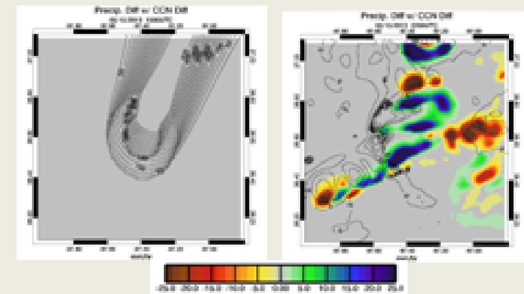


- On weekdays, bimodal distribution of traffic on roads peaking during rush hours.
  Longer morning rush → Broader distribution
  Shorter, more intense evening rush → Narrower distribution
- Weekend has more singular model with a mid-day peak.
- Traffic is directly correlated to CO_2 emission profiles.

RAMS

- The Regional Atmospheric Modeling System (RAMS) is a sophisticated non-hydrostatic weather model capable of modeling city-scale weather modification (Cotton et al. 2003; Pielke et al. 1992).
- Bin-approximating cloud physics: 8-microphysical species, 3 cloud-nucleating aerosols (Saleeby and Cotton 2008, 2005; Meyers et al. 1997).
- Town Energy Budget (TEB) urban canopy model uses same inputs as urban model to generate traffic. The Simple Photochemical Module chemistry generates urban aerosol output from traffic directly based on hourly emission rates (Masson 2000; Freitas et al. 2005).
- Traffic profile is used as input for aerosol generation.
- This study utilizes the RAIL method in the idealized city (Schmid and Niyogi 2013): The 10km radius city is placed in the path of an oncoming rain system.

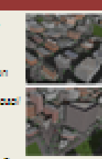
Weather Simulation Results



- City emits cloud nucleating aerosols as prescribed by traffic simulation.
- As precipitation approaches from the east it interacts with aerosol field simultaneous with land surface.
- Aerosol interaction leads to heavier rain at outset: downpour at edge of city compared to a homogeneous aerosol field.

Implications & Conclusions

- This is the first study to directly couple a traffic-flow simulation model to a weather model.
- Next step: Modeling traffic response to induced precipitation.
- Spatially heterogeneous aerosols are necessary to properly simulate cloud interaction with city.
- Rain slows down traffic, increases rush hour duration. *Does it significantly affect aerosol generation?*
- Traffic model can be modified to represent different road types.
- What is the best city layout to minimize inadvertent weather modification?
- How can we use smart planning to best improve traffic and weather in current cities?



References

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Acknowledgements

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