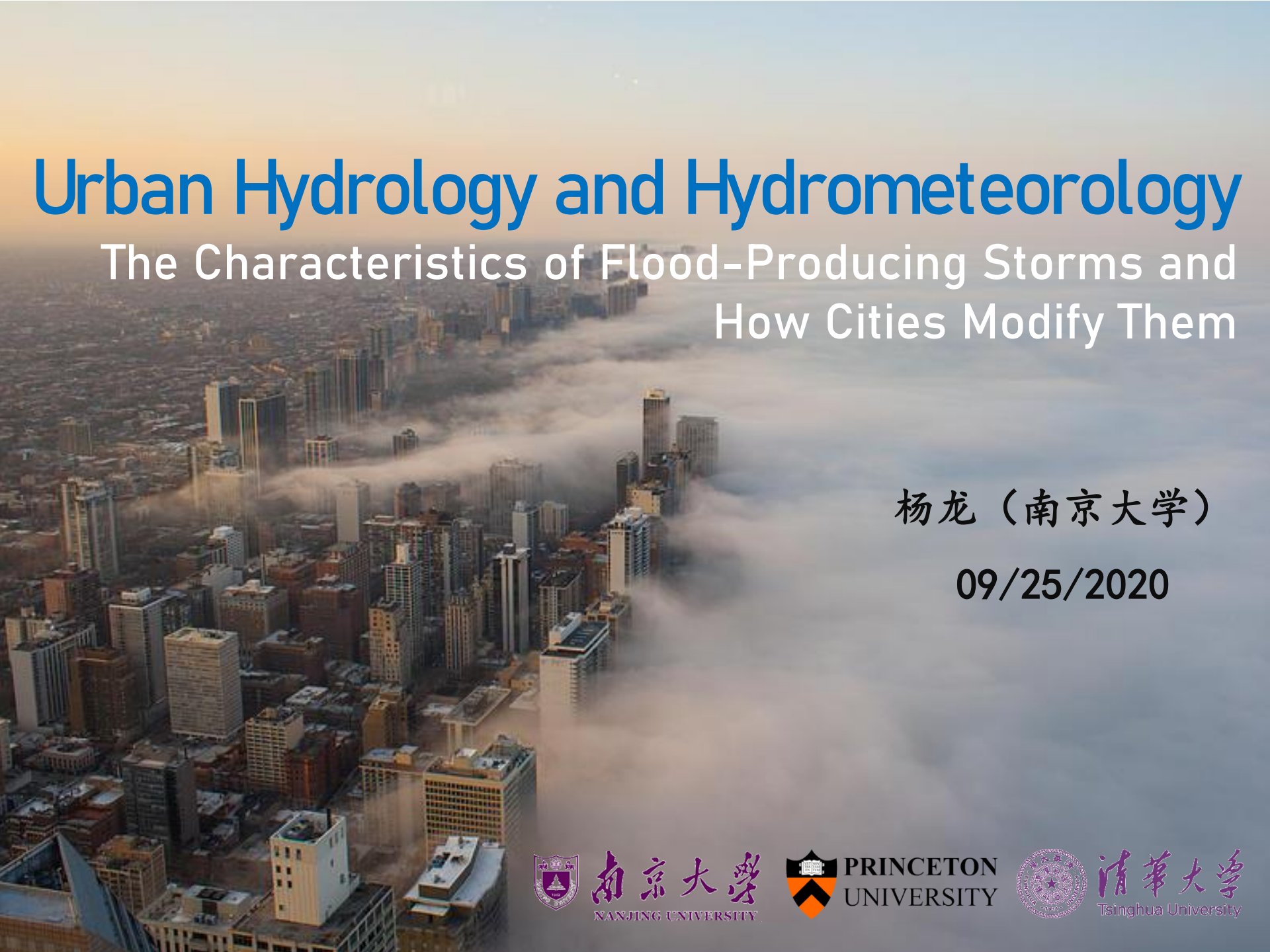
Urban Hydrology and Hydrometeorology

The Characteristics of Flood-Producing Storms and How Cities Modify Them

杨龙（南京大学）

09/25/2020



南京大學 NANJING UNIVERSITY

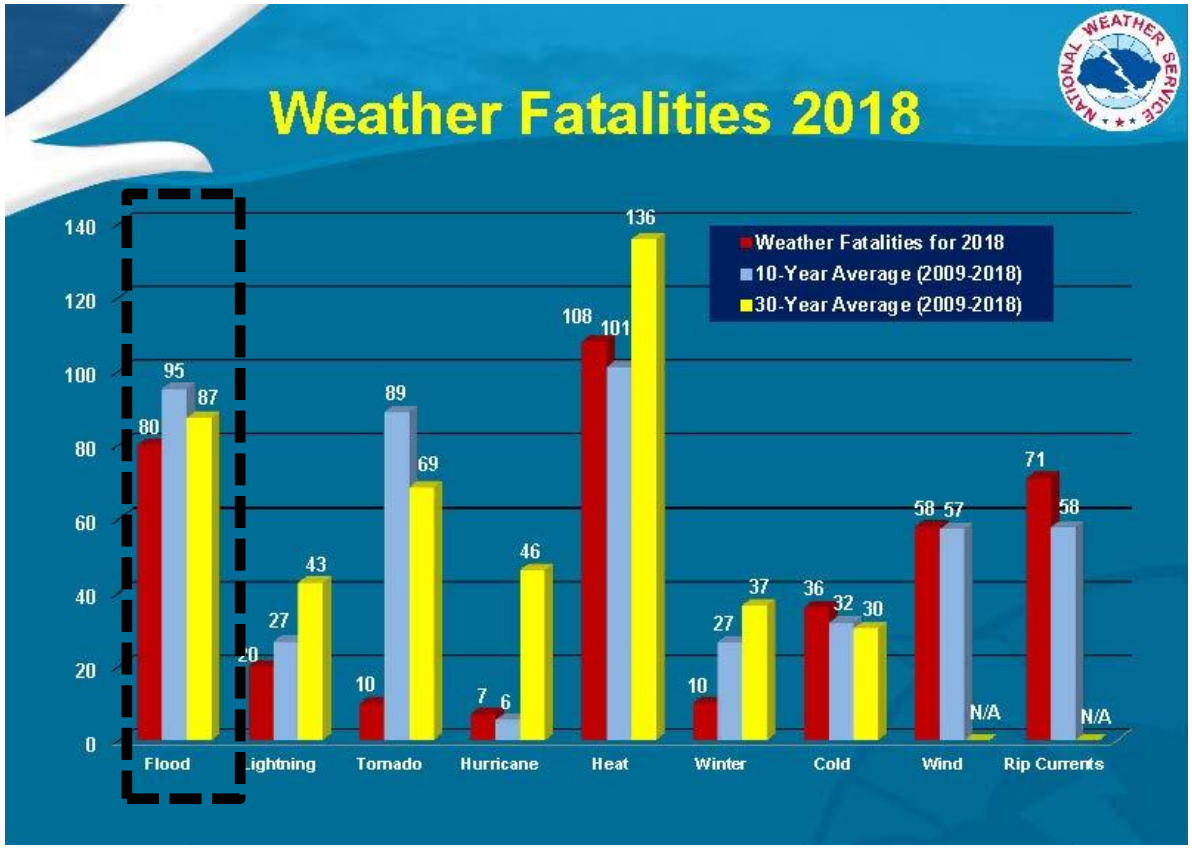
PRINCETON UNIVERSITY

清華大學 Tsinghua University


2.5% areas of the earth host
>50% of the world population
58% of Chinese population lives in cities

Extreme rainfall and urban flooding

Increasing urban flood hazards tied to climate change and population growth



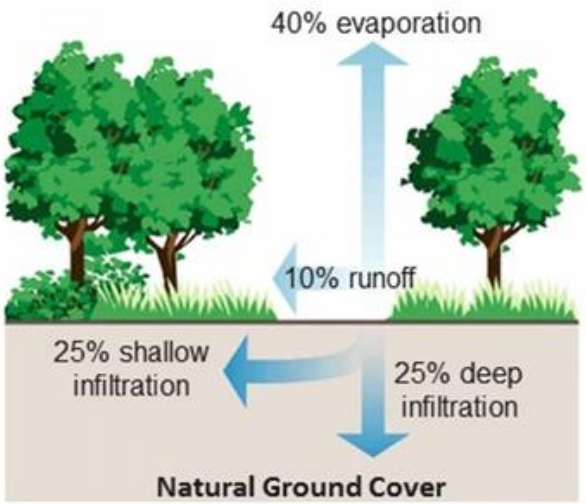
National Weather Service, 2019

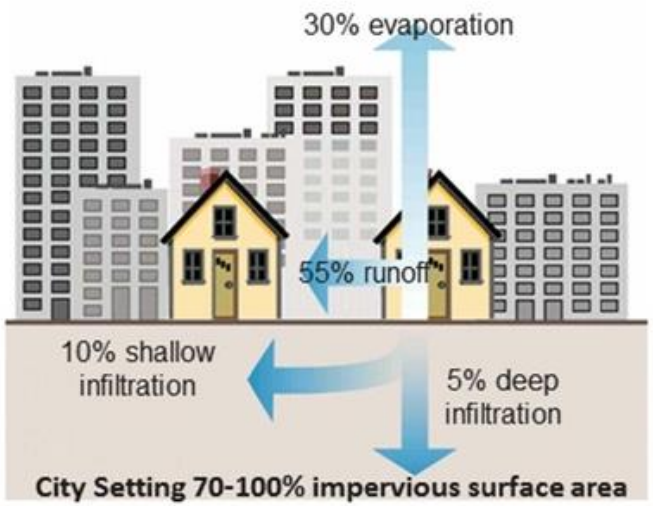
The Ellicott city flood

A quintessential example of devastating floods in cities

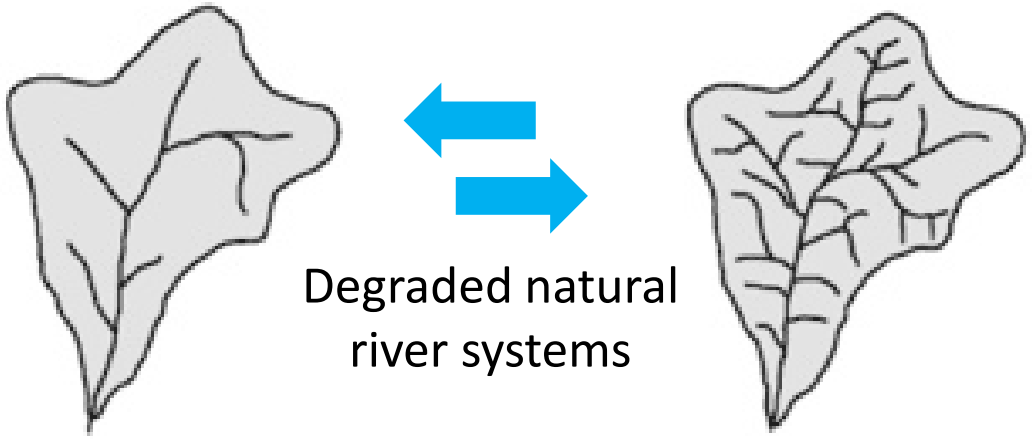
Urban impacts on hydrological cycle

Three changed aspects: Partition, Storage, and Release

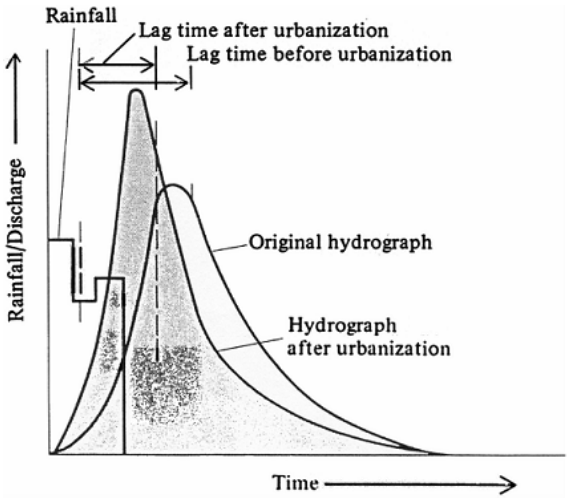




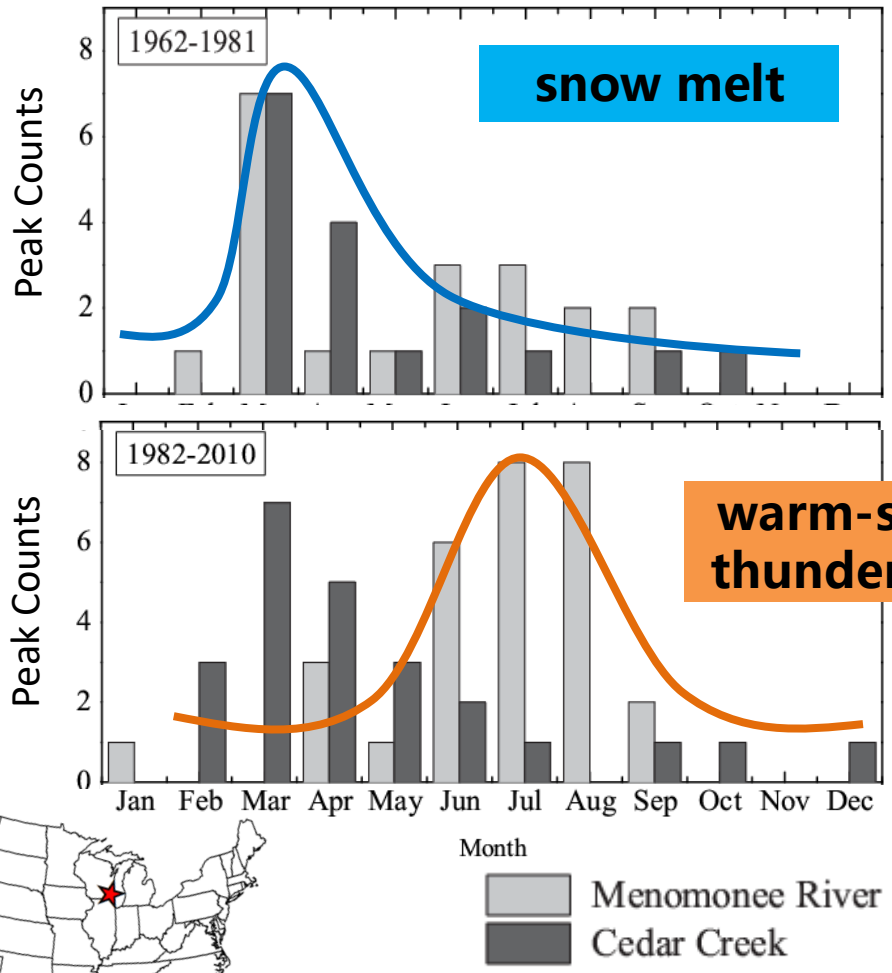
More storm runoff
Larger flood peak
Shorter response time
Shorter duration
……

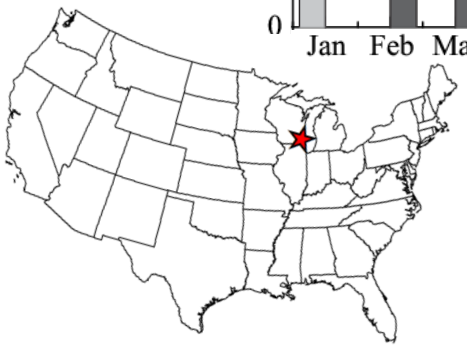


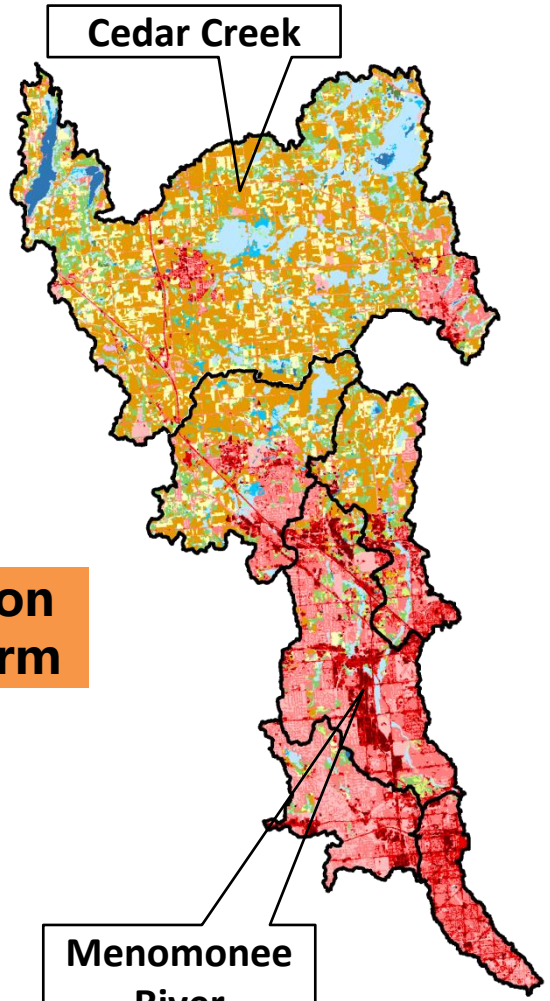
Degraded natural river systems



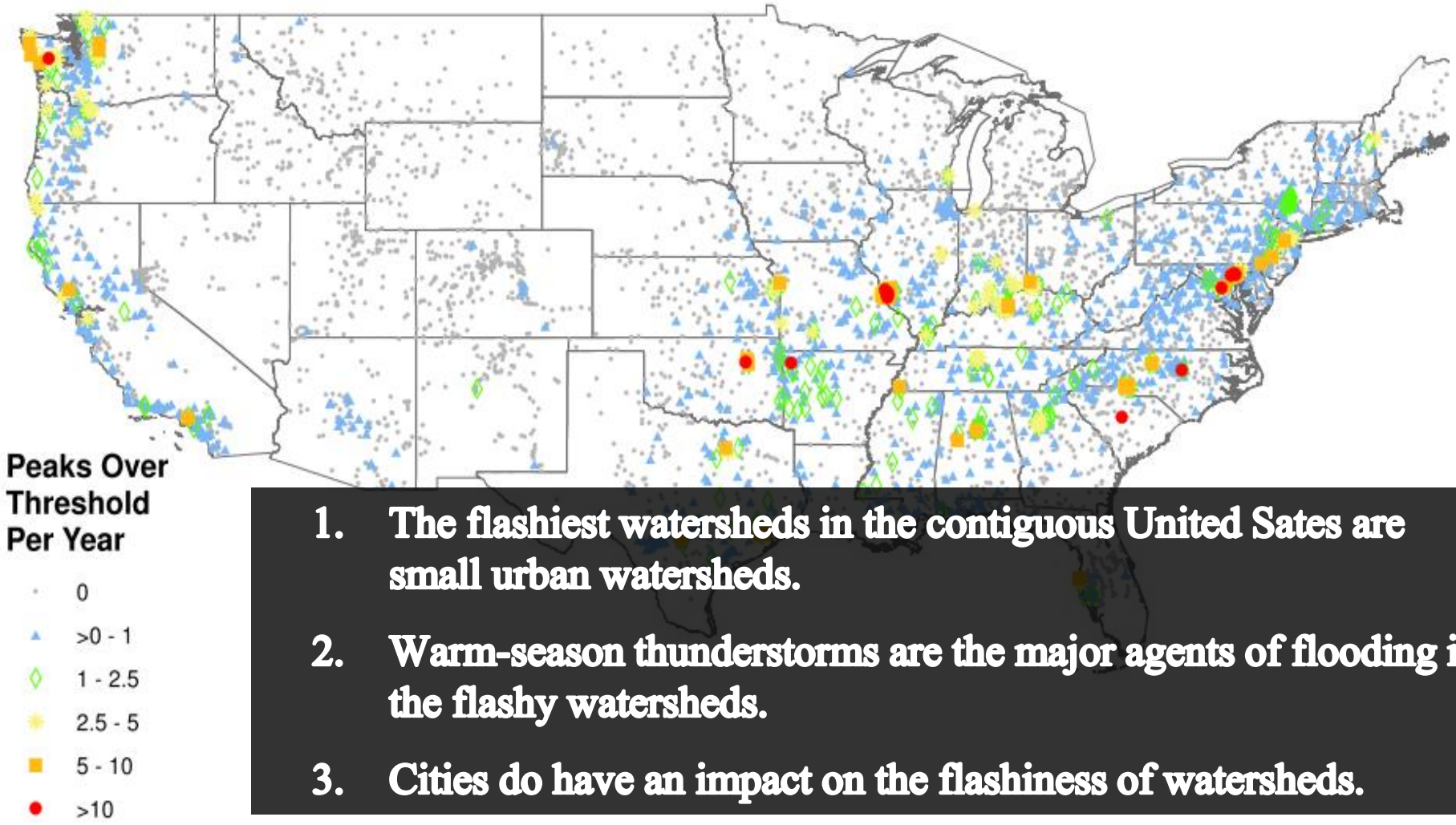
The changed flood seasonality associated with urban expansion







Where are the "flashiest" watersheds over the CONUS?



1. The flashiest watersheds in the contiguous United Sates are small urban watersheds.
2. Warm-season thunderstorms are the major agents of flooding in the flashy watersheds.
3. Cities do have an impact on the flashiness of watersheds.

(Smith et al., JHM, 2015)

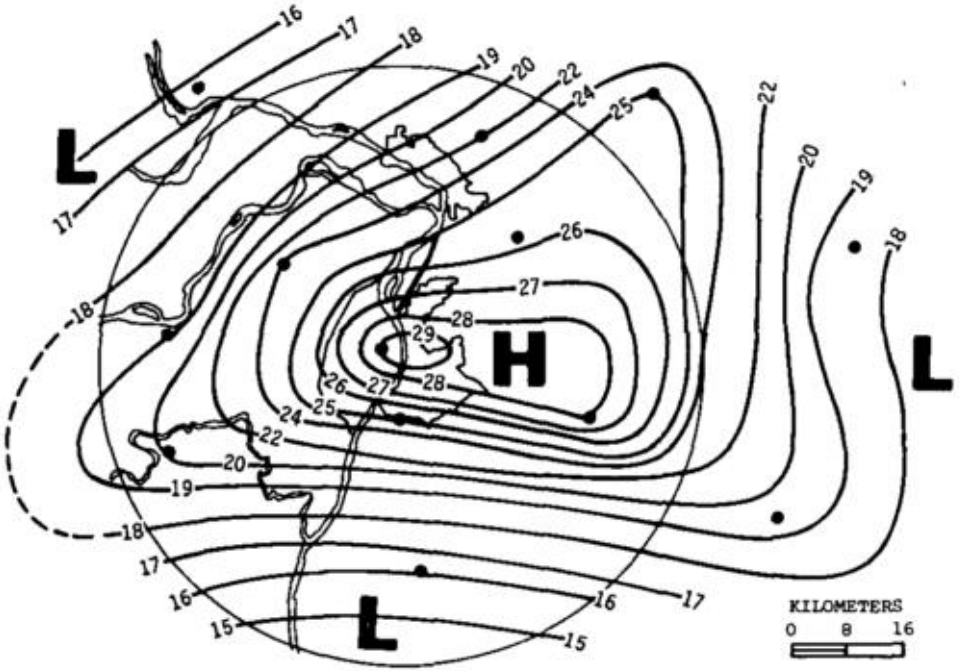
Do cities modify storms (e.g., frequency, intensity, etc.) that lead to more extreme rainfall?

Yes, cities also modify thunderstorms

Metropolitan Meteorological Experiment (METROMEX, 1970s)

A pioneering project that expands the research domain of urban hydrology

Average summer thunder days



Frequency of heavy rainfall

(Changnon., BAMS, 1971)

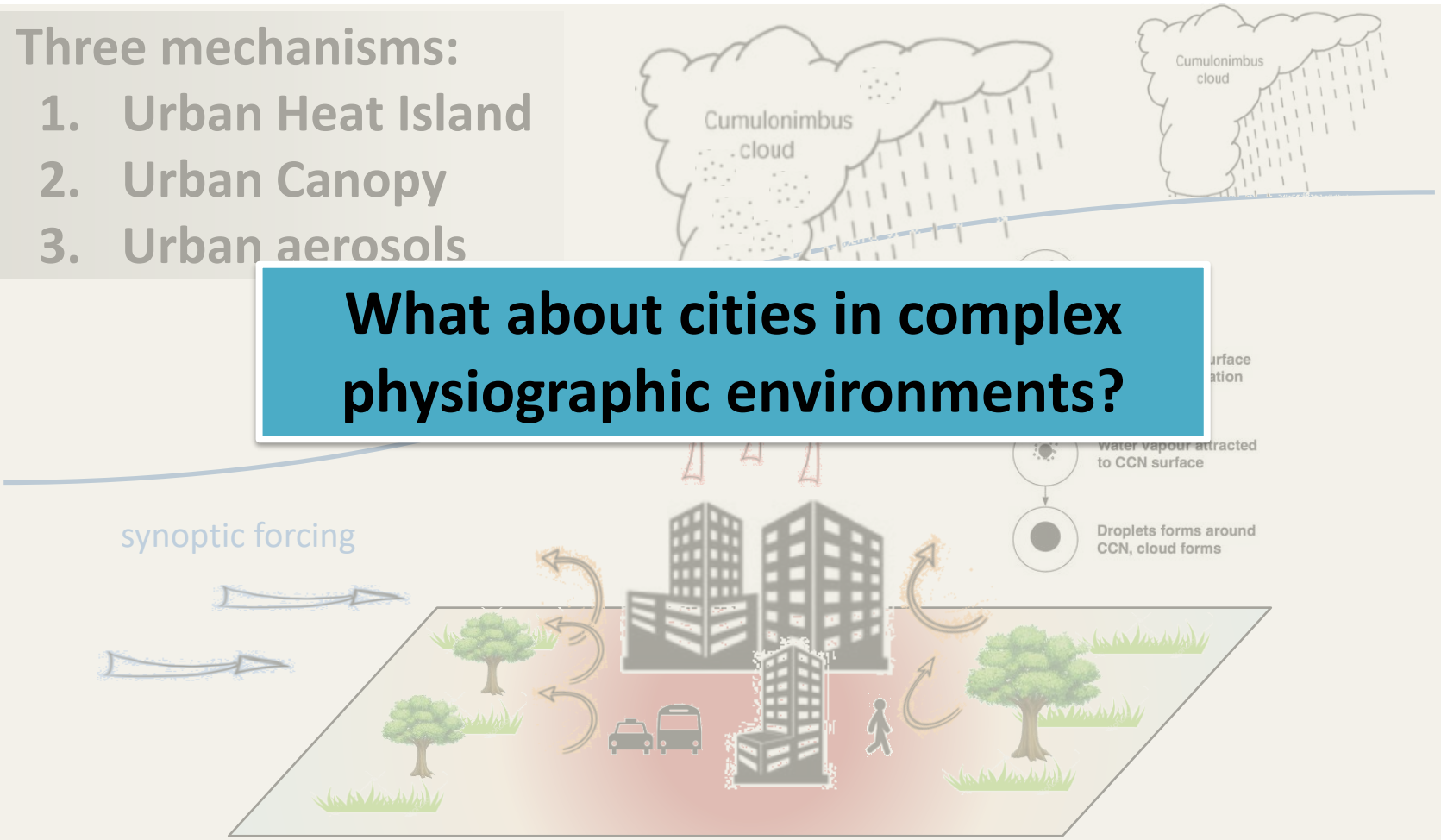
Why do cities modify thunderstorms?

Legacies from the METROMEX studies (till present)

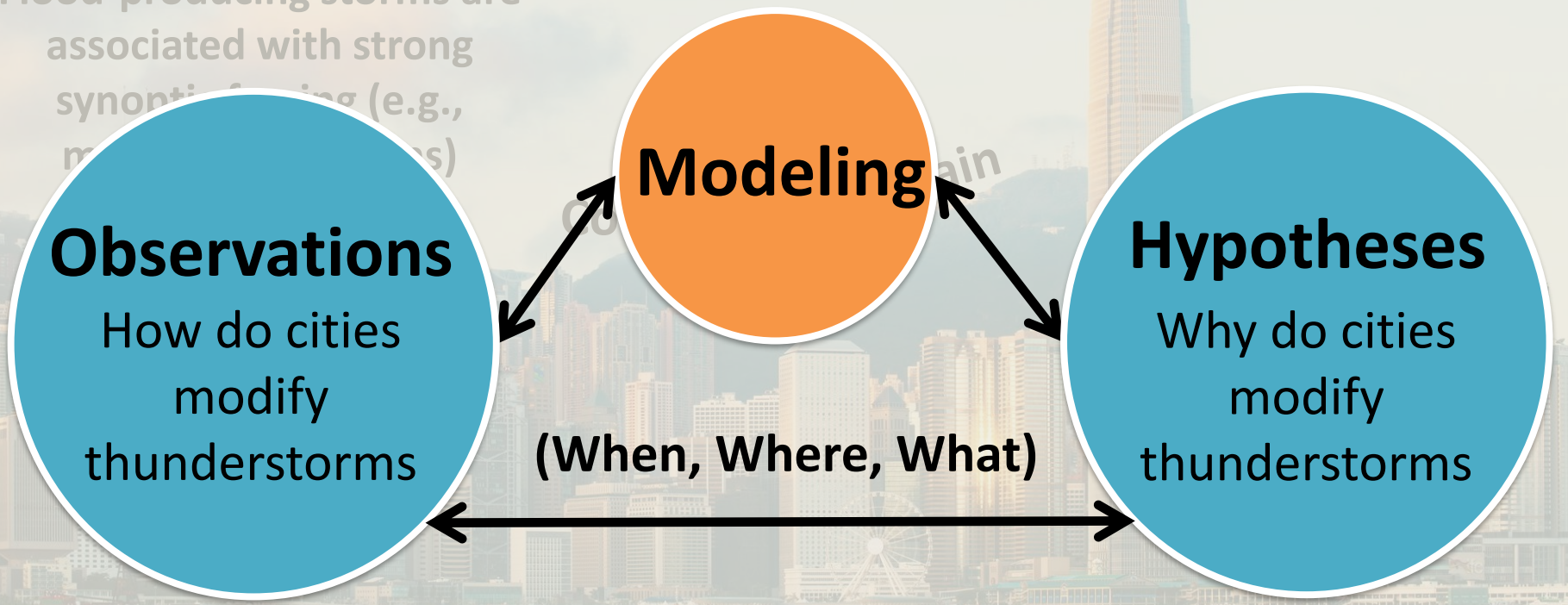
Three mechanisms:

1. Urban Heat Island
2. Urban Canopy
3. Urban aerosols

What about cities in complex physiographic environments?



Cities are not isolated from the environment

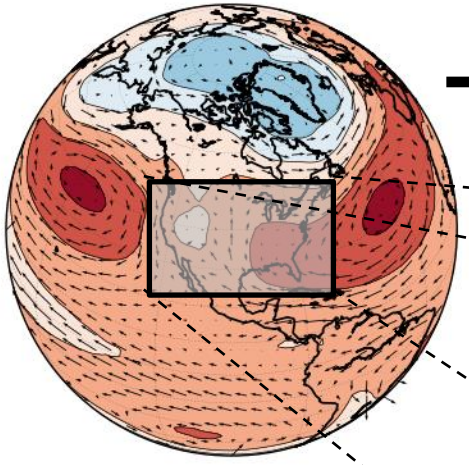


Skyline of Hong Kong

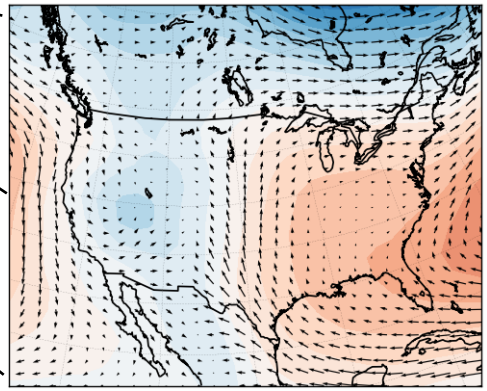
The physical modeling system

A spectrum of coupled scales

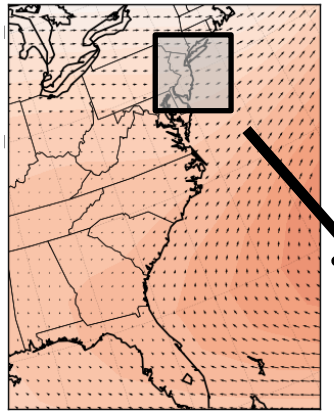
Global scale

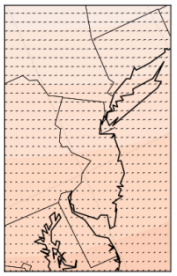


Continental scale

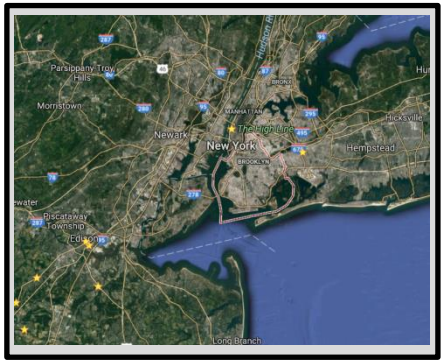


Regional scale



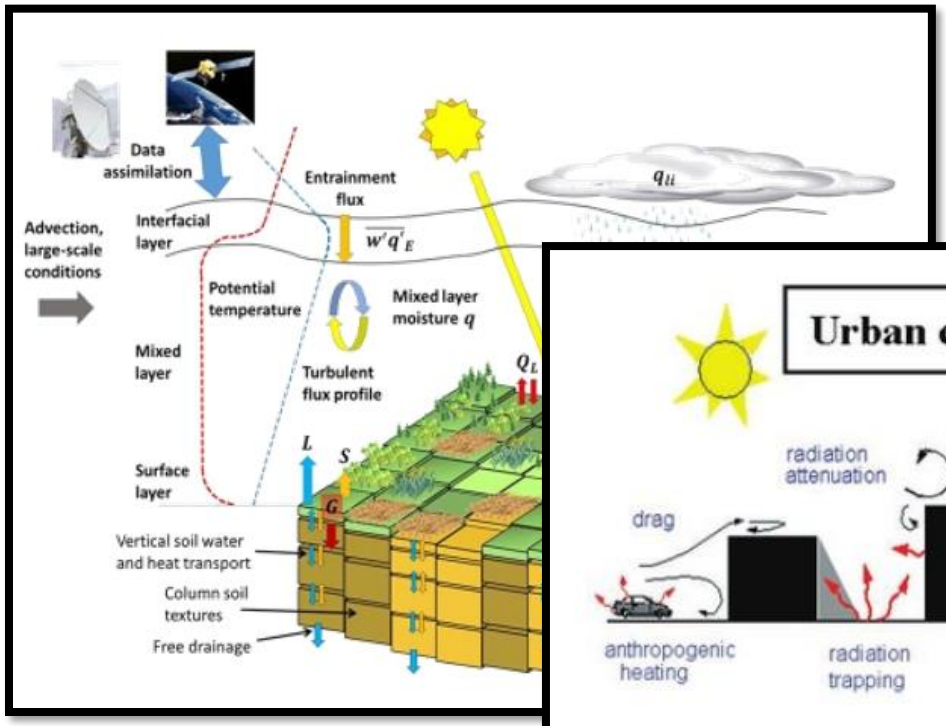


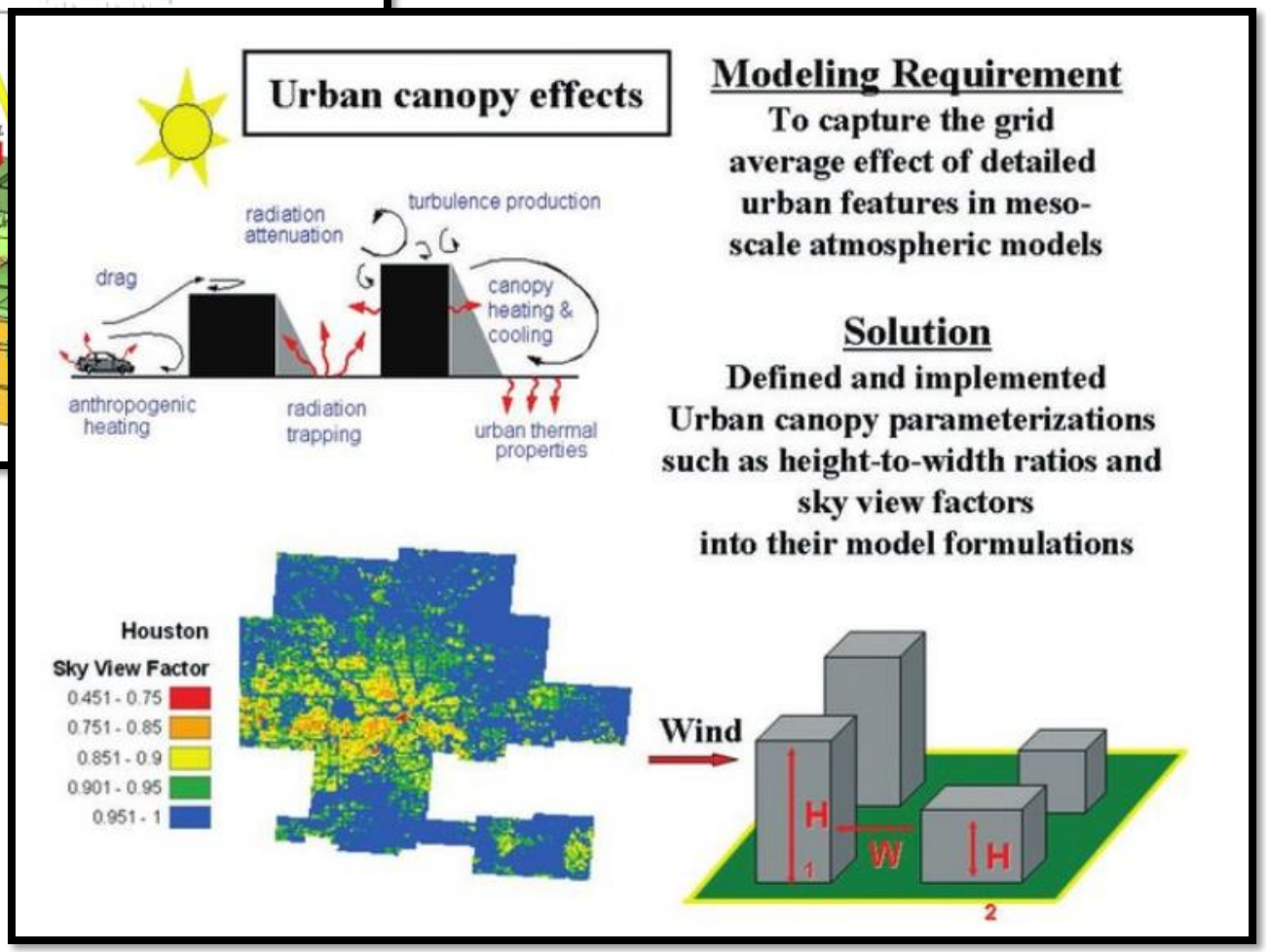
City scale



Local scale/micro-scale

Define "cities" in earth system models





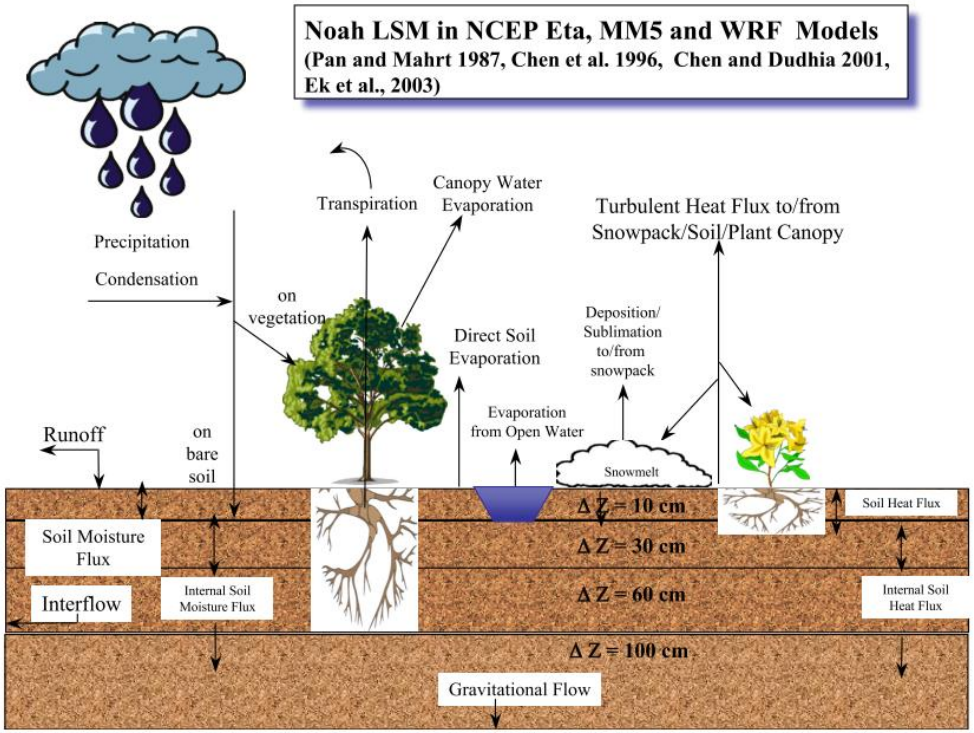
- Anthropogenic heat
- Hydrological process
- Building energy
- etc.

(Chen et al., IJOC, IJOC)

Weather Research and Forecasting (WRF) model

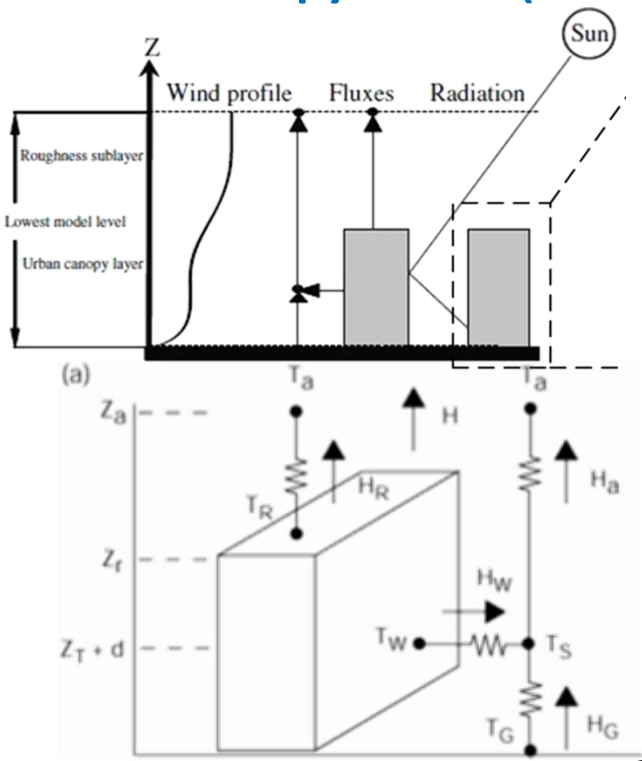
- Widely used “community model” for both research and operational forecasting
- Nested model enables coupling of continental-scale to city-scale features

Natural Surfaces: Noah Land Surface Model (NOAH)



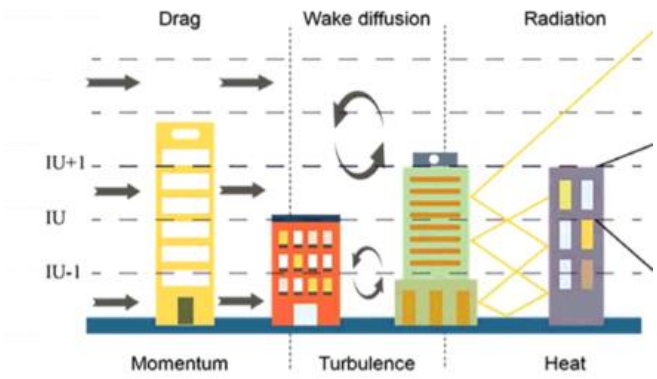
(Chen et al. 2011; Kusaka et al. 2004)

Urban Surfaces: Urban Canopy Model (UCM)

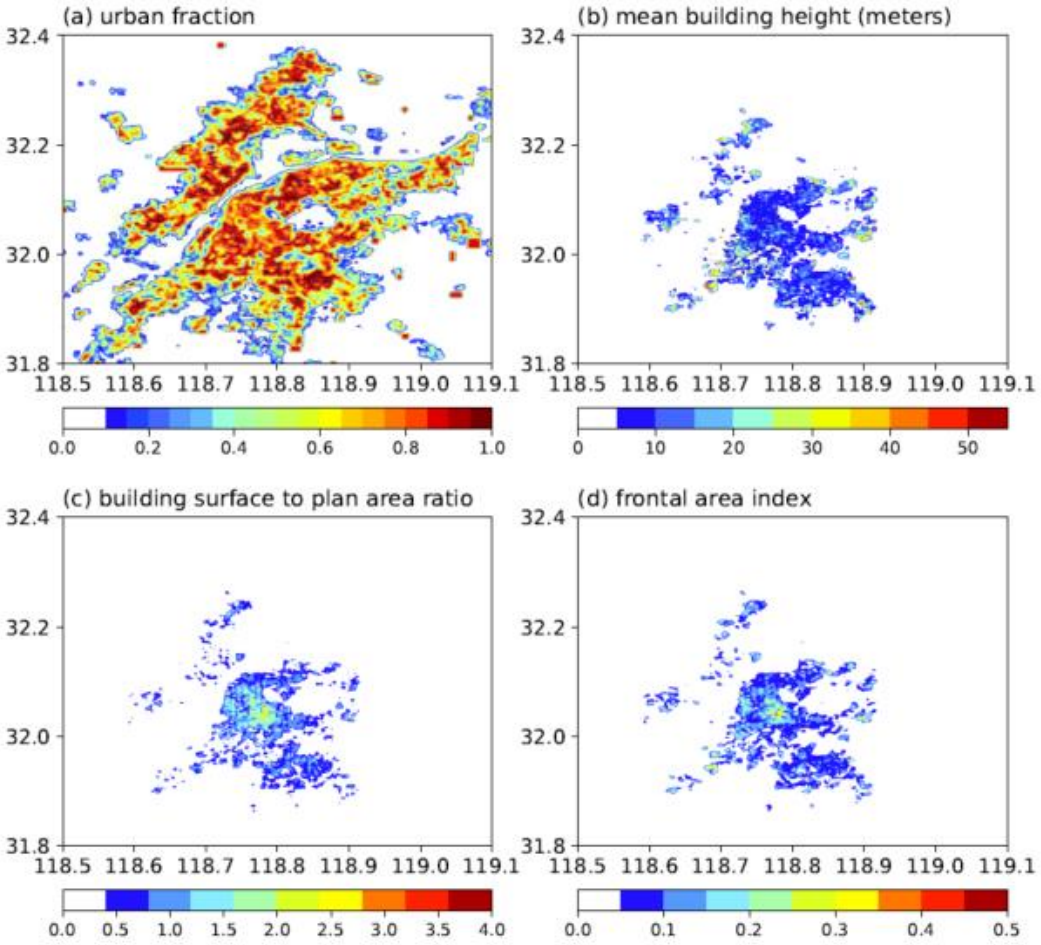


Weather Research and Forecasting (WRF) model

Improved representations of heterogeneous urban surfaces through incorporating urban canopy parameters



Building Effect Parametrizations (BEP)



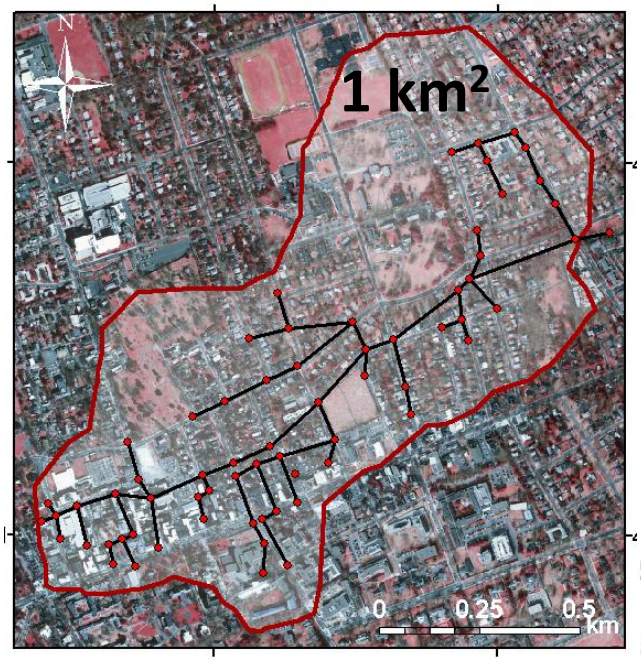
Today's themes

- What are the key **characteristics of storms** that produce flooding in small urban watersheds (1-100km^2)?

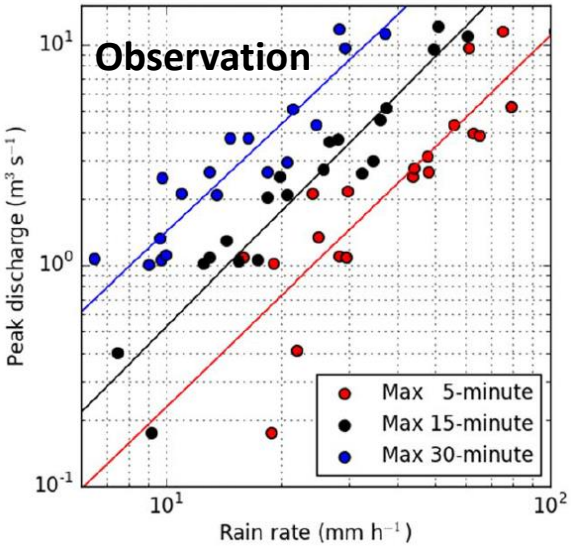
- How does **complex terrain interact with the urban environment** to control the regional distribution of extreme rainfall?

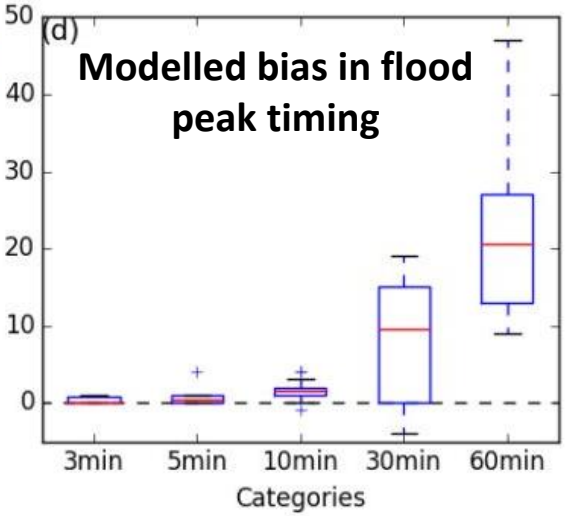
Storm structure and evolution

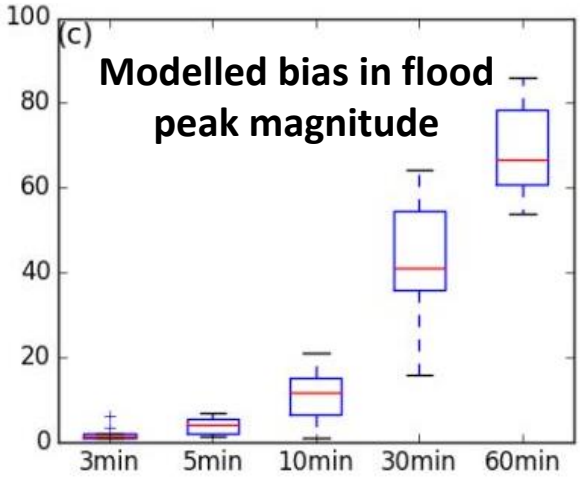
Sub-hourly rainfall variability is critical for urban floods



Harry's Brook, Princeton





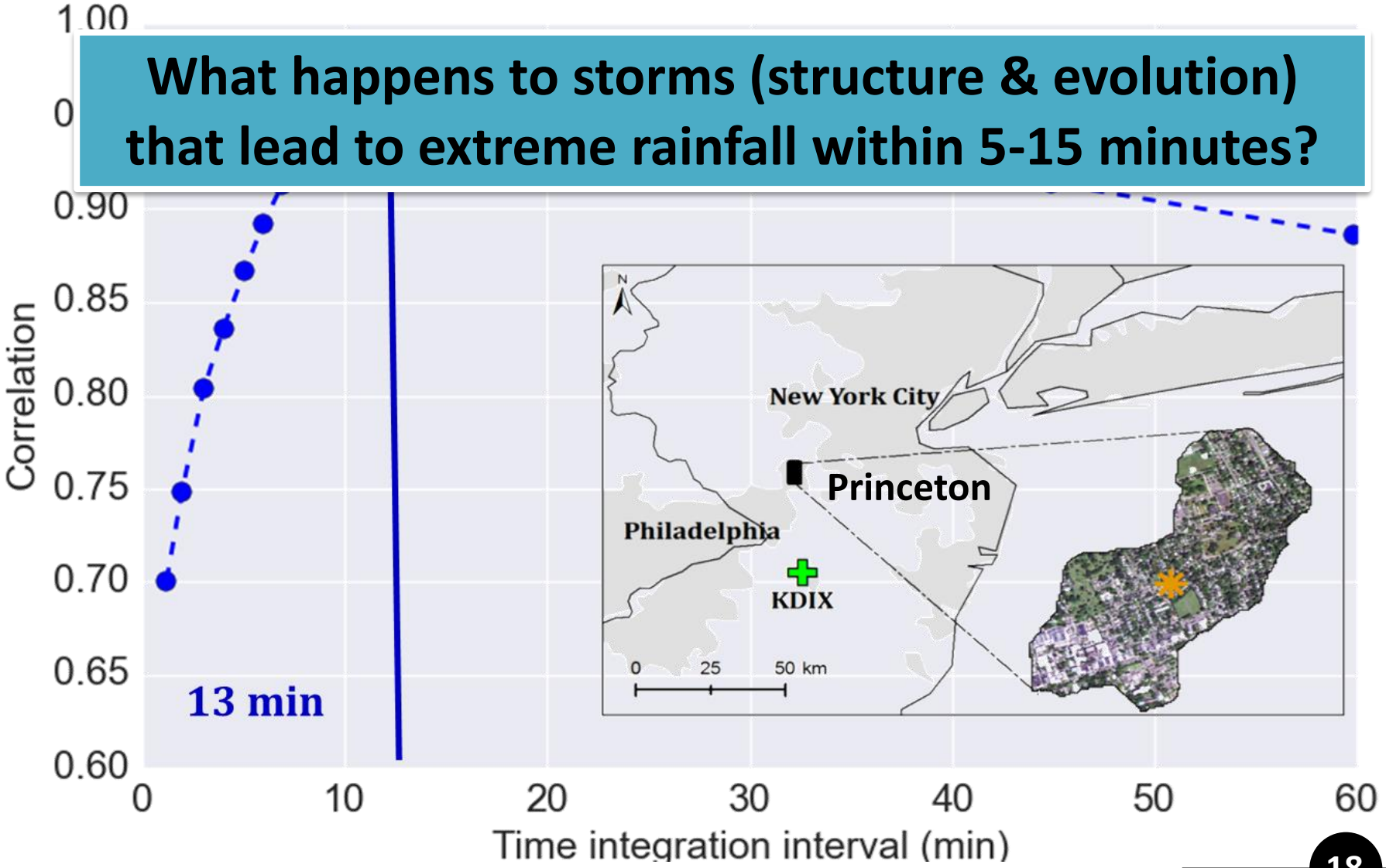


(Yang et al., WRR, 2016)

Story of a small urban watershed (1 km^2)

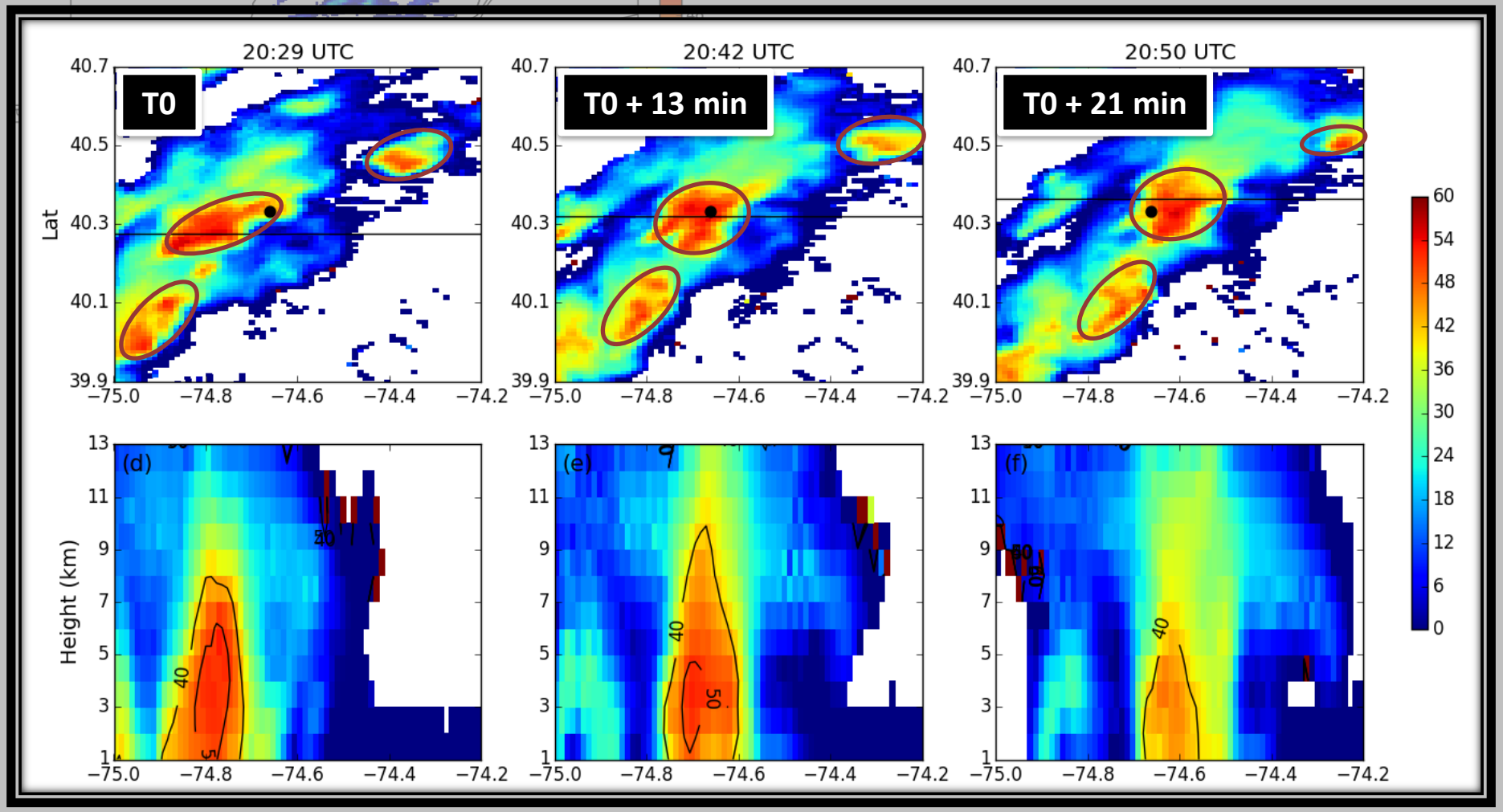
Rainfall variability at "short time" scales is critical for urban flooding

What happens to storms (structure & evolution) that lead to extreme rainfall within 5-15 minutes?



Storm cell: a 3D continuum of rain pixels with radar reflectivity exceeding 40 dBZ (~25 mm/h)

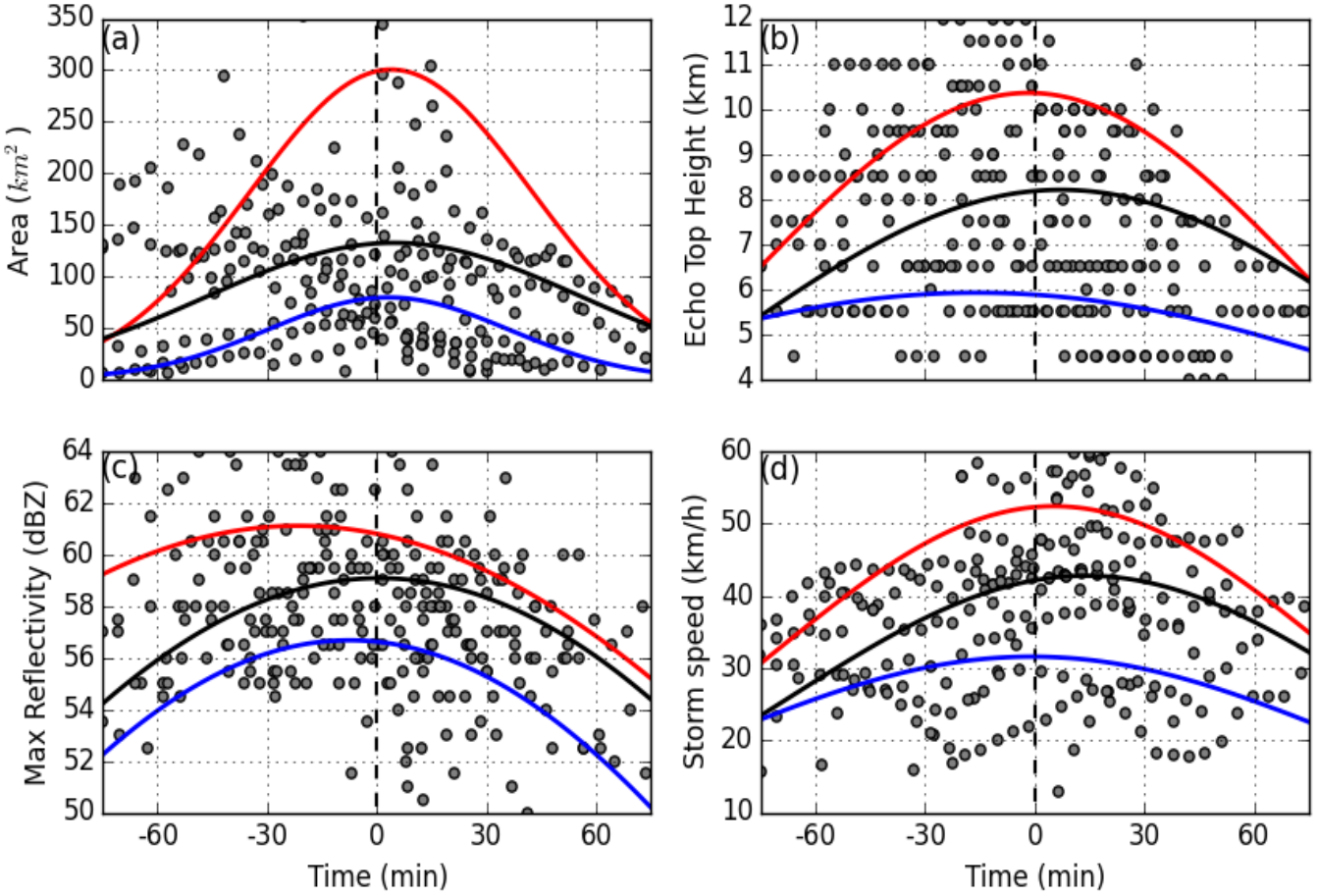
Collapsing storm cells → temporal rainfall variability



(Yang et al., JGR, 2016)

Story of a small urban watershed (1 km^2)

Composite analyses: structure and evolution



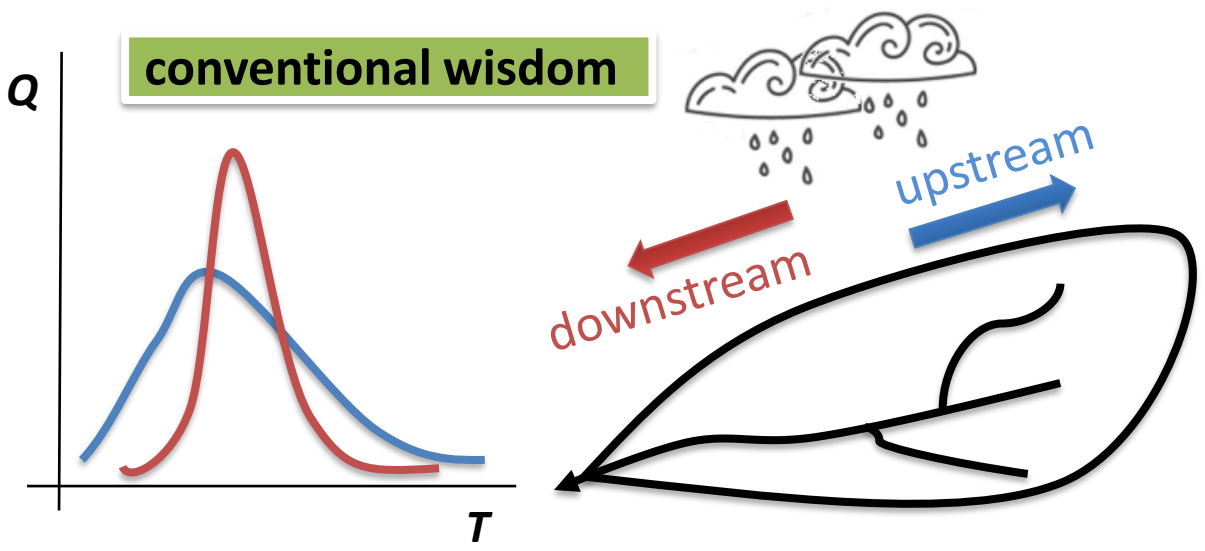
Area	Echo top
Max dBZ	Storm speed

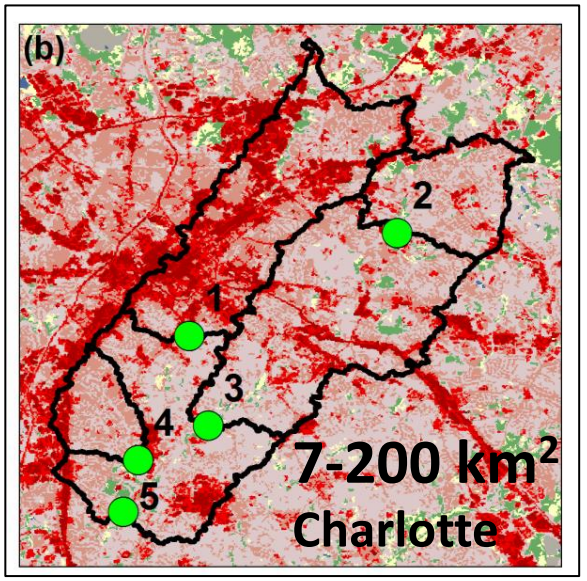
75th percentile
50th percentile
25th percentile

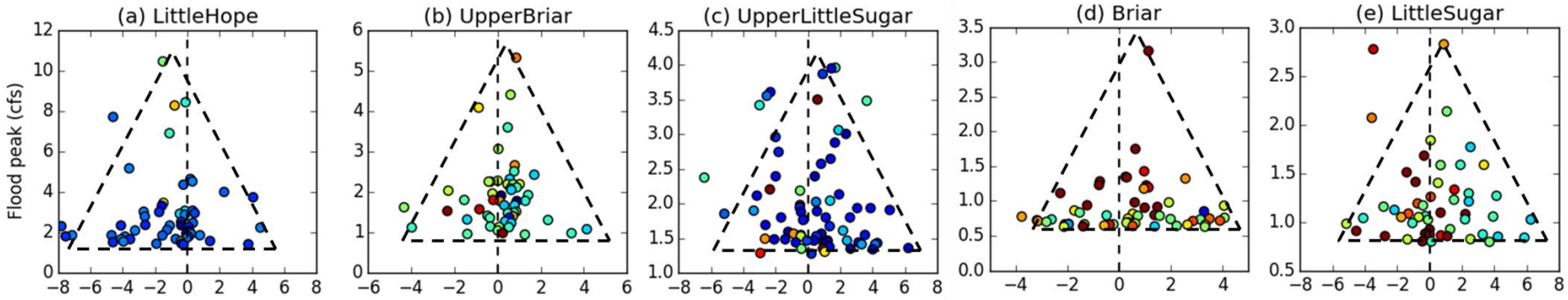
- Drops of echo top height and maximum radar reflectivity
- Slow storms following peak rain rate

Story of multiple small urban watersheds

Storm size as well as storm motion relative to drainage network







gradient of flow distance

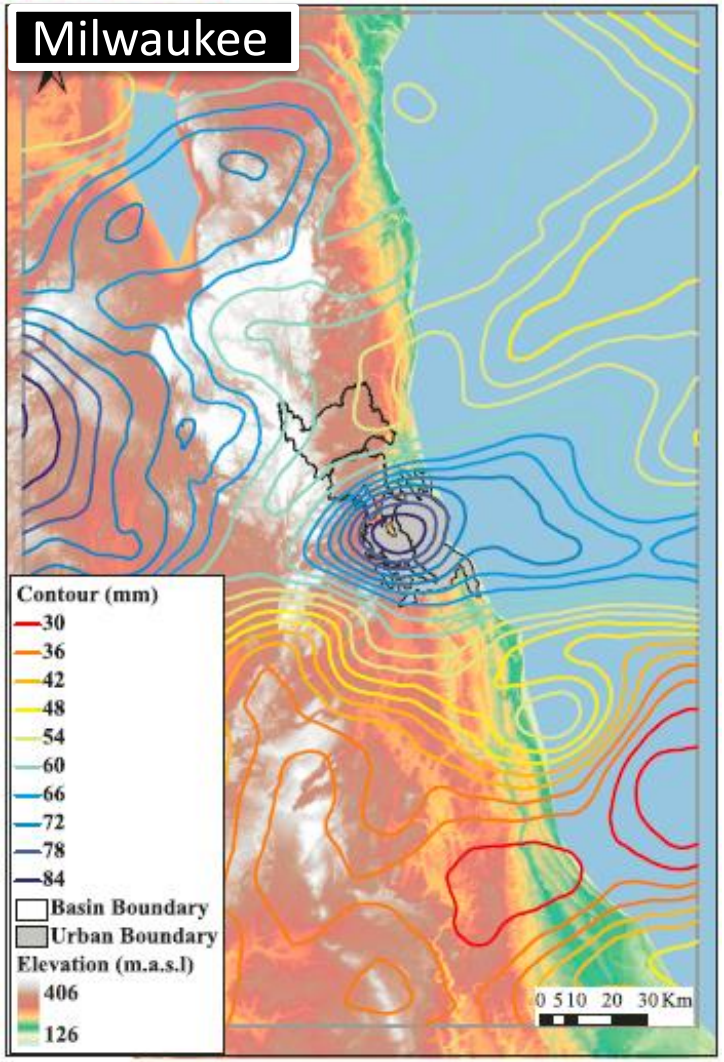
Today's themes

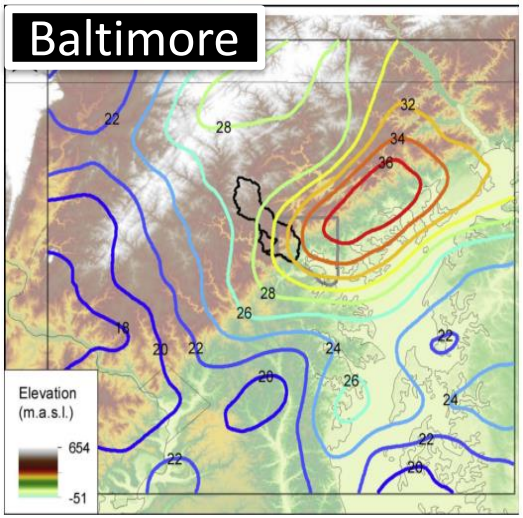
- What are the key characteristics of storms that produce flooding in small urban watersheds (1-100km^2)?

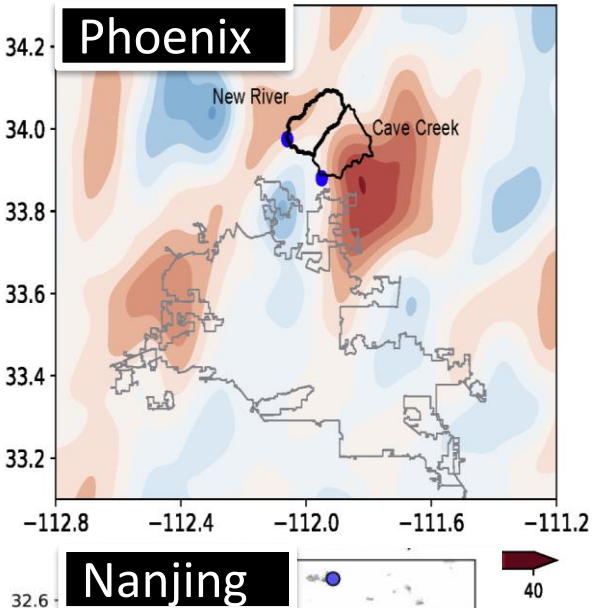
- How does land-water boundaries/complex terrain interact with the urban environment to control the regional distribution of extreme rainfall?

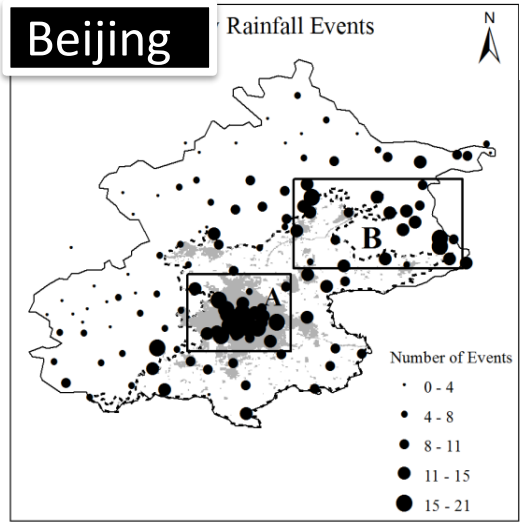
Urban impacts on flood-producing storms

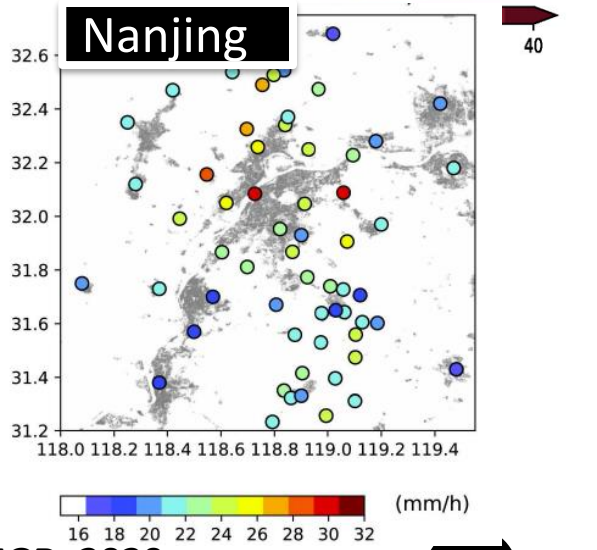
Observational evidence around the world









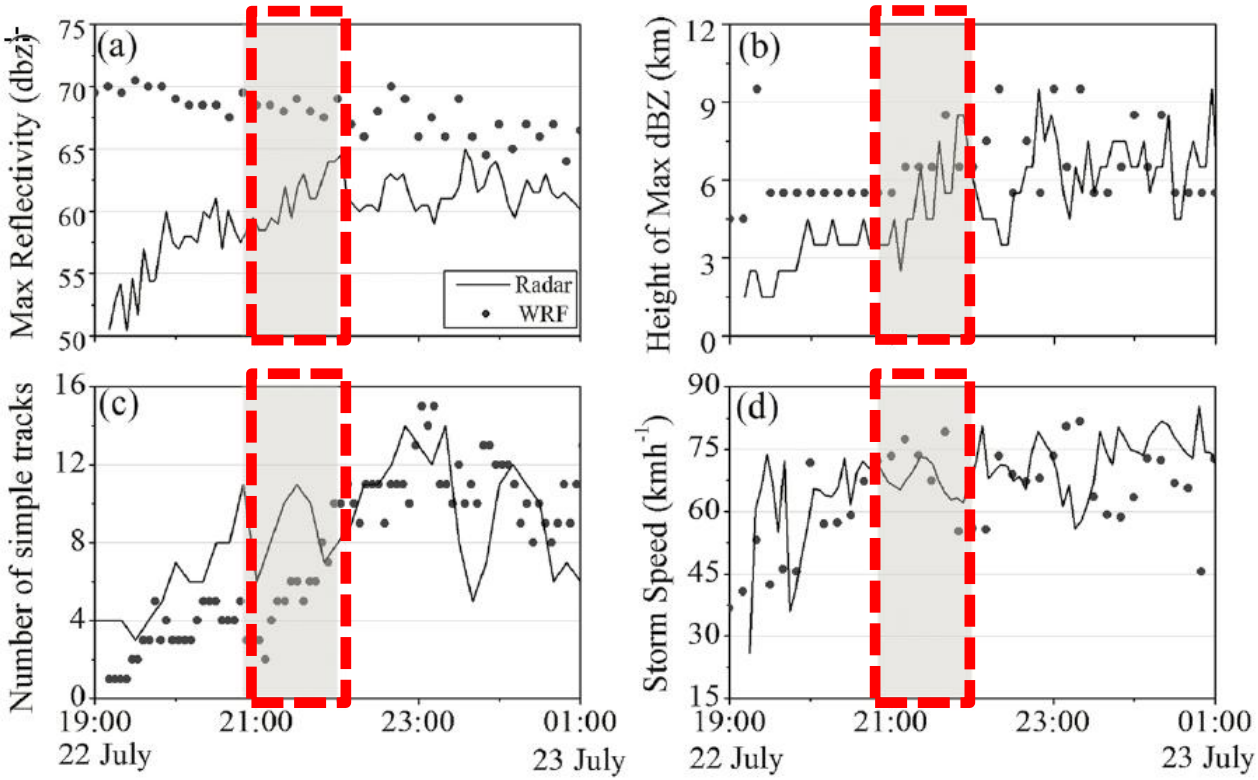


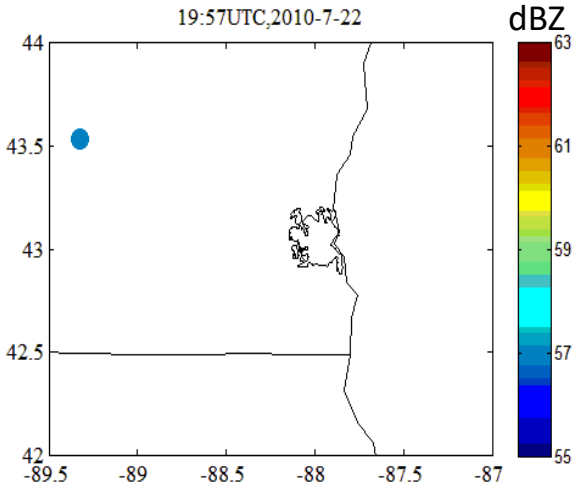
Smith et al., WRR, 2012; Yang et al., JHM, 2013; JGR, 2014; GRL, 2019; JGR, 2020

The changing behaviors of storm cells

High-resolution simulations + storm tracking

Cities modify the structure and evolution of convective storm cells

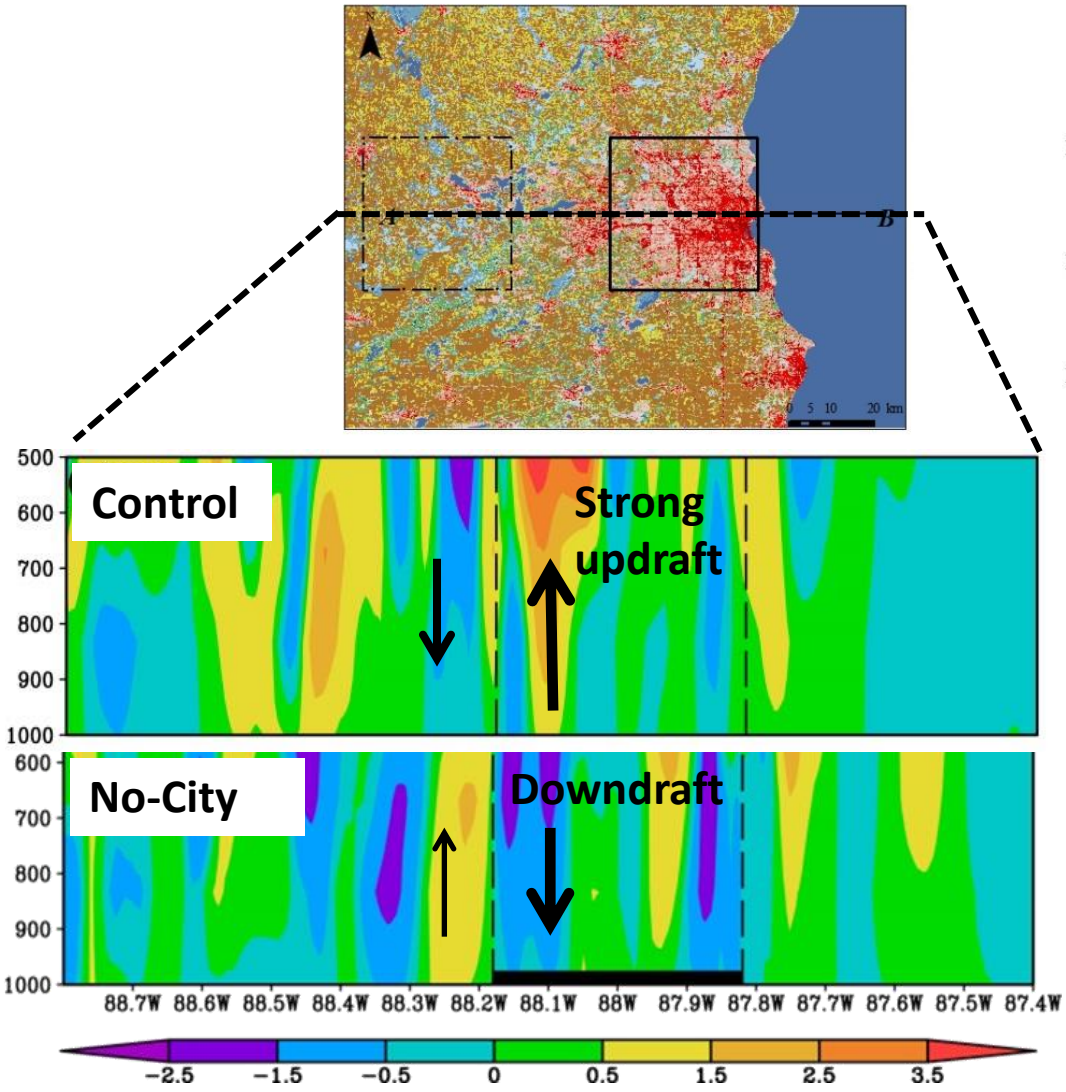


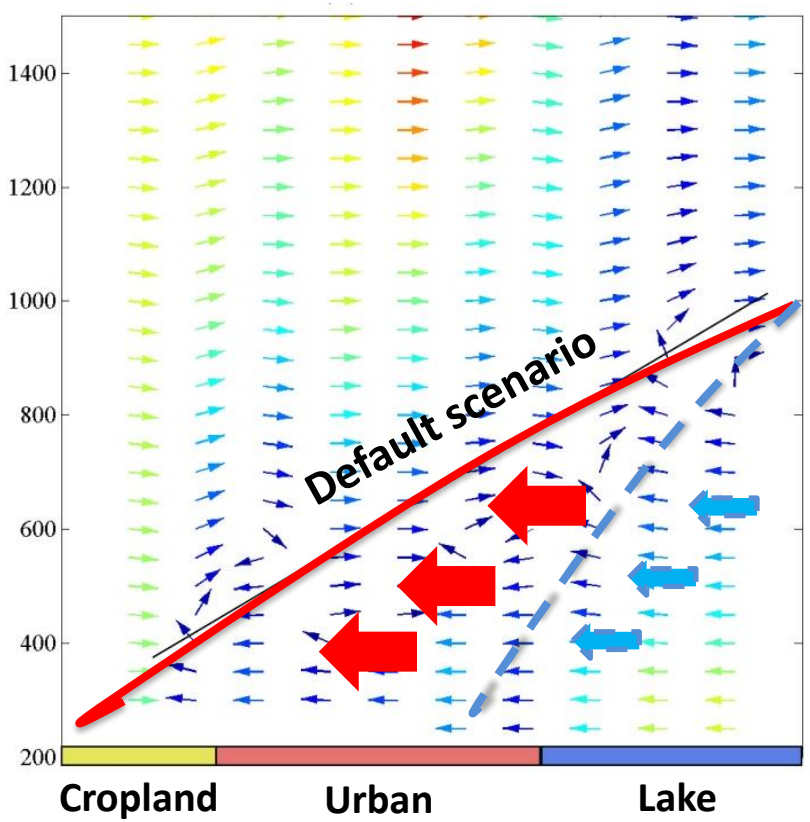


- More storm cells
- Higher intensity
- Slower motion

Flood-producing storms in complex terrain

Interactions of UHI and lake-breeze circulation

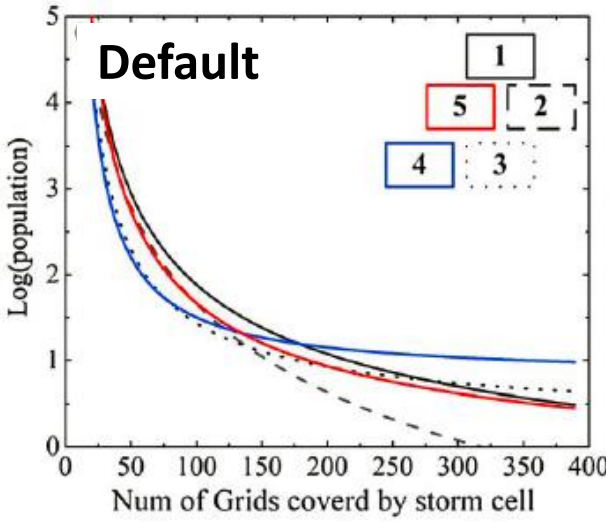


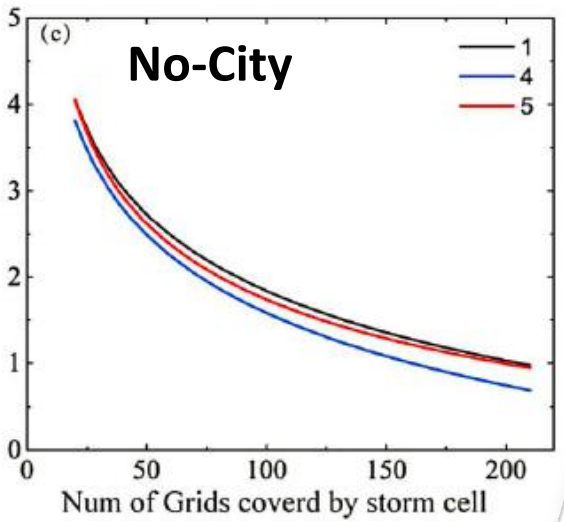


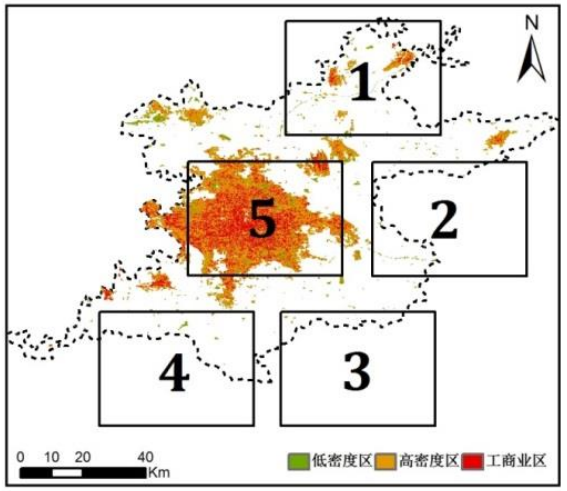
The changing behaviors of storm cells

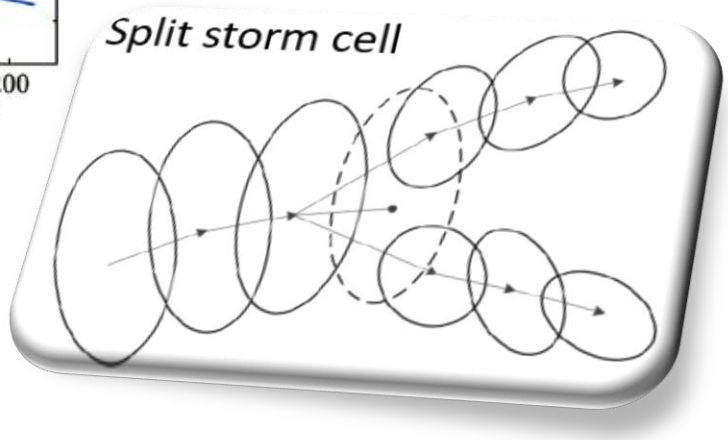
Regional climate simulations + Storm identification

Cities change the frequency distribution of convective storm cells





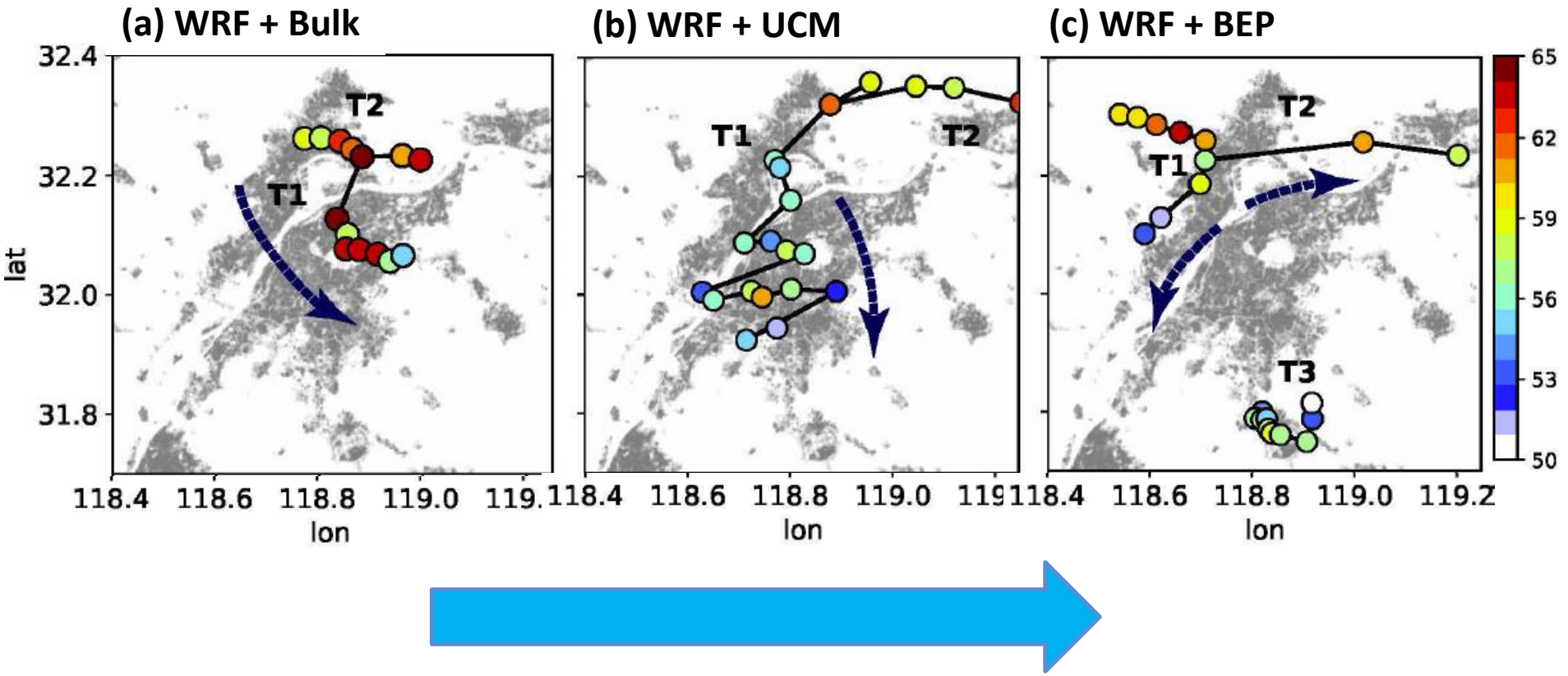




- Splitting storm cells indicate strong convection within urban boundary layer

The changing behaviors of storm cells

High-resolution simulations + Storm tracking

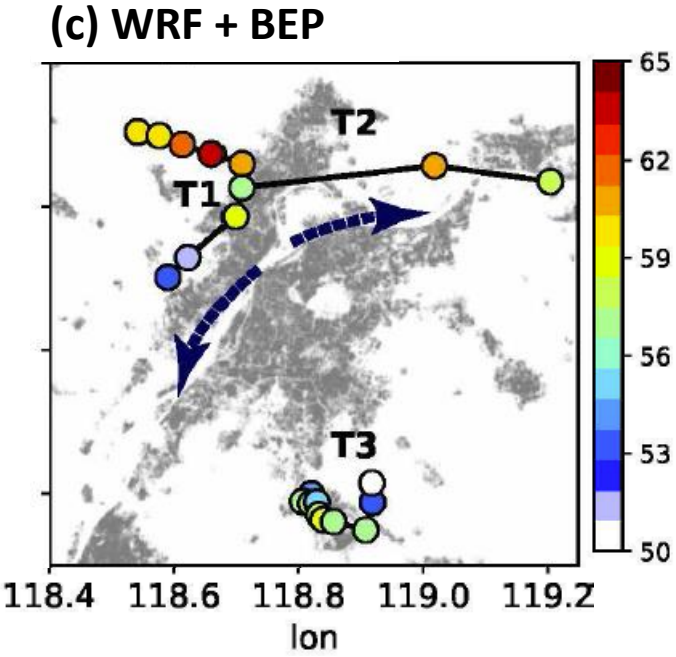


Improved representation of urban morphology (especially its vertical dimension)

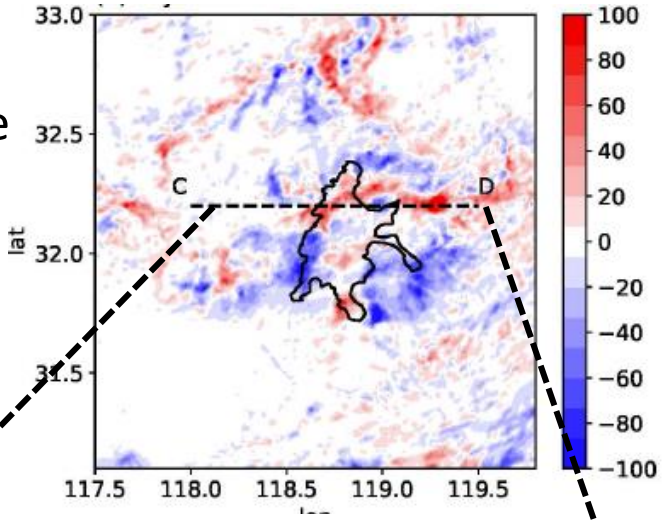
➔ Contrasting behaviors of storm evolution over cities

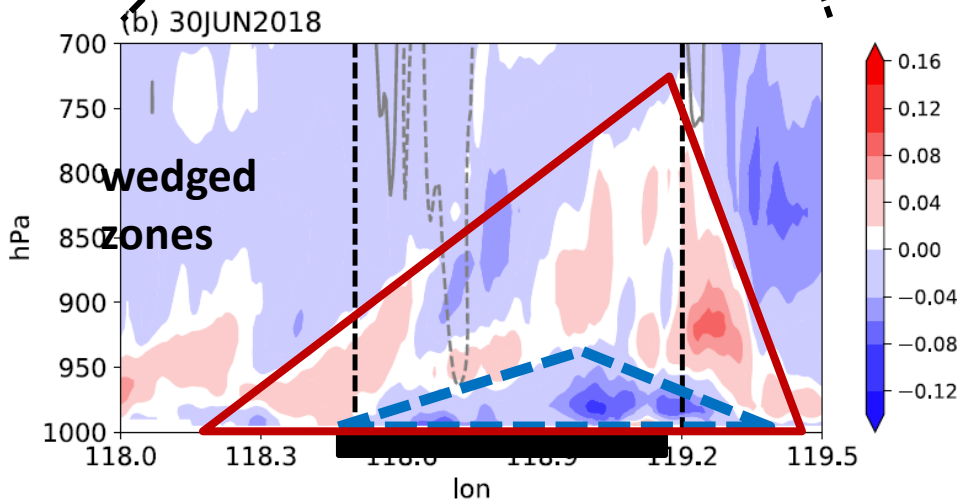
The changing behaviors of storm cells

High-resolution simulations + Storm tracking



moisture convergence

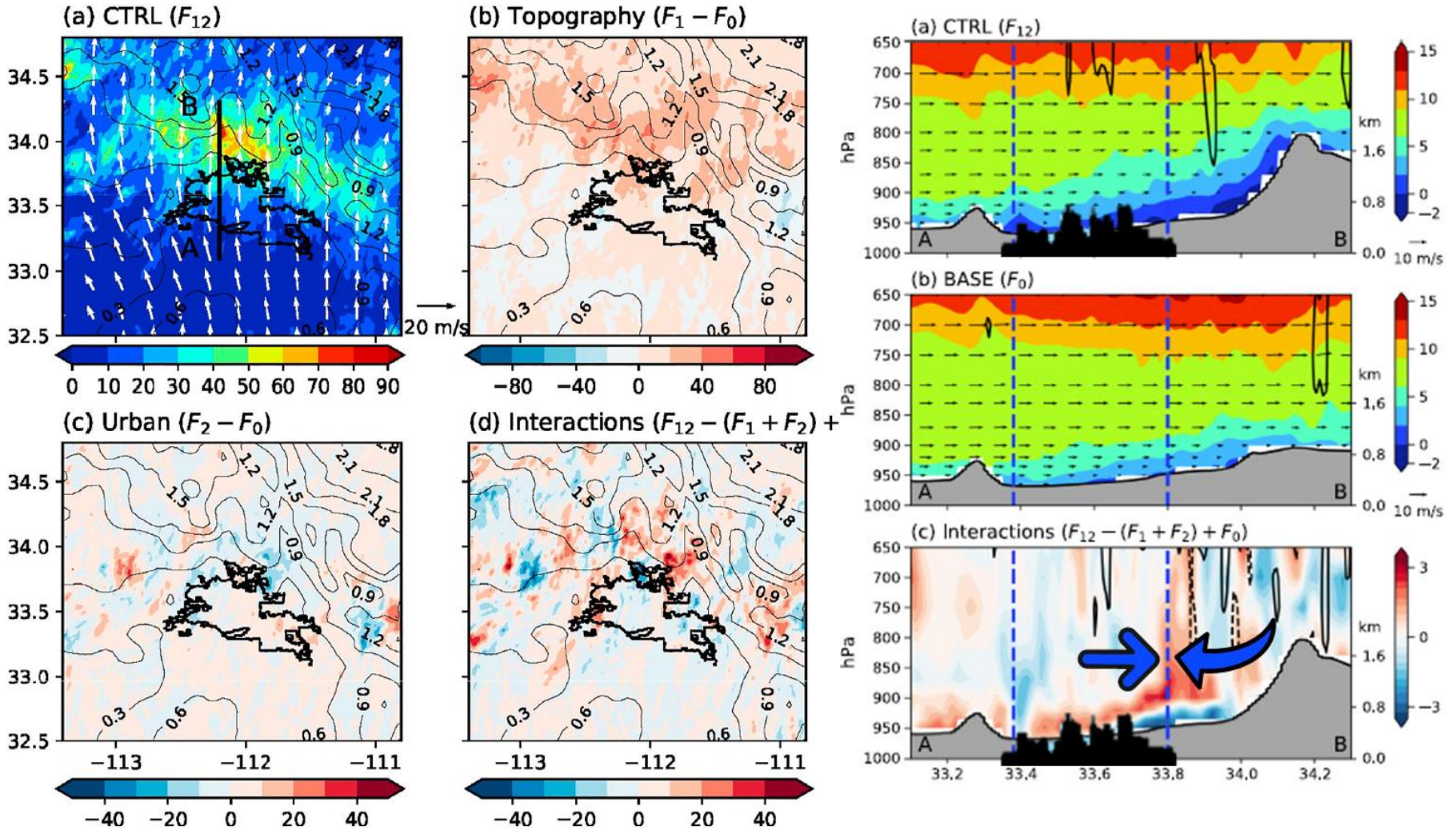




- **Urban barrier ➔ bifurcated moisture flux and intensified convection**

Flood-producing storms in complex terrain

Interactions of outflow boundary and urban circulation



Summary

1. Flood response in small urban watersheds: characteristics of storms and determining factors

The Princeton urban watershed (1 km^2)

- Short-scale rainfall variability is critical for urban flooding
- "collapsing" storm cells; slow-moving storm systems

The Charlotte urban watersheds (<200 km^2)

- Slow storm motion relative to drainage network

2. Flood-producing storms in cities: role of land-water boundaries and complex terrain

- Urban signatures in heavy rainfall anomalies in "complex" cities
- Cities change the behaviors of convective storm cells
- Preferred location of convergence due to Interactions of lake breeze / outflow boundary and synoptic flow over cities

LOOKING FORWARD:

What are the remaining challenges?

1. Better characterization of urban extreme rainfall

(e.g., dual-pol radars)

2. Better representations of cities in numerical models

(e.g., UCPs, improved urban parameterizations)

3. Effective communications with flood hydrologists

(e.g., storm now-casting schemes, design storm based on advanced techniques, such as stochastic storm transitions)

Thanks!

Email: yanglong@nju.edu.cn