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Multi-scale Modelling of Chicago Urban Heat Island and Climate-Change Impacts

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Chicago Heat Island

Chicago and Climate Change

- July 1995 heat wave in Chicago
  - Deadliest in American history – 465 deaths
  - Record breaking 41.1 °C at Midway Airport
- Chicago Climate Action Plan
  - Adaptation for future conditions
- Need a tool that can link climate change to UHI
  - Must capture all the relevant scales of UHI

Outline

1. Multi-scale modelling approach
2. Model validation
3. Climate-change applications
    a) Lake breeze
    b) Pedestrian comfort
    c) Pollutant dispersion
    d) Building energy
4. Conclusions

MULTI-SCALE MODELLING

Multi-scale Modelling

- Statistical downscaling
  - Faces limitations – past observations and regime shifts
- Dynamical downscaling
  - Requires multi-model chain
  - Global to regional to city to micro-scales
    - finest scales required for pedestrians and buildings
  - Thus far efforts have only covered portion of this chain
- We seek to bridge all these scales

Multi-scale Modelling

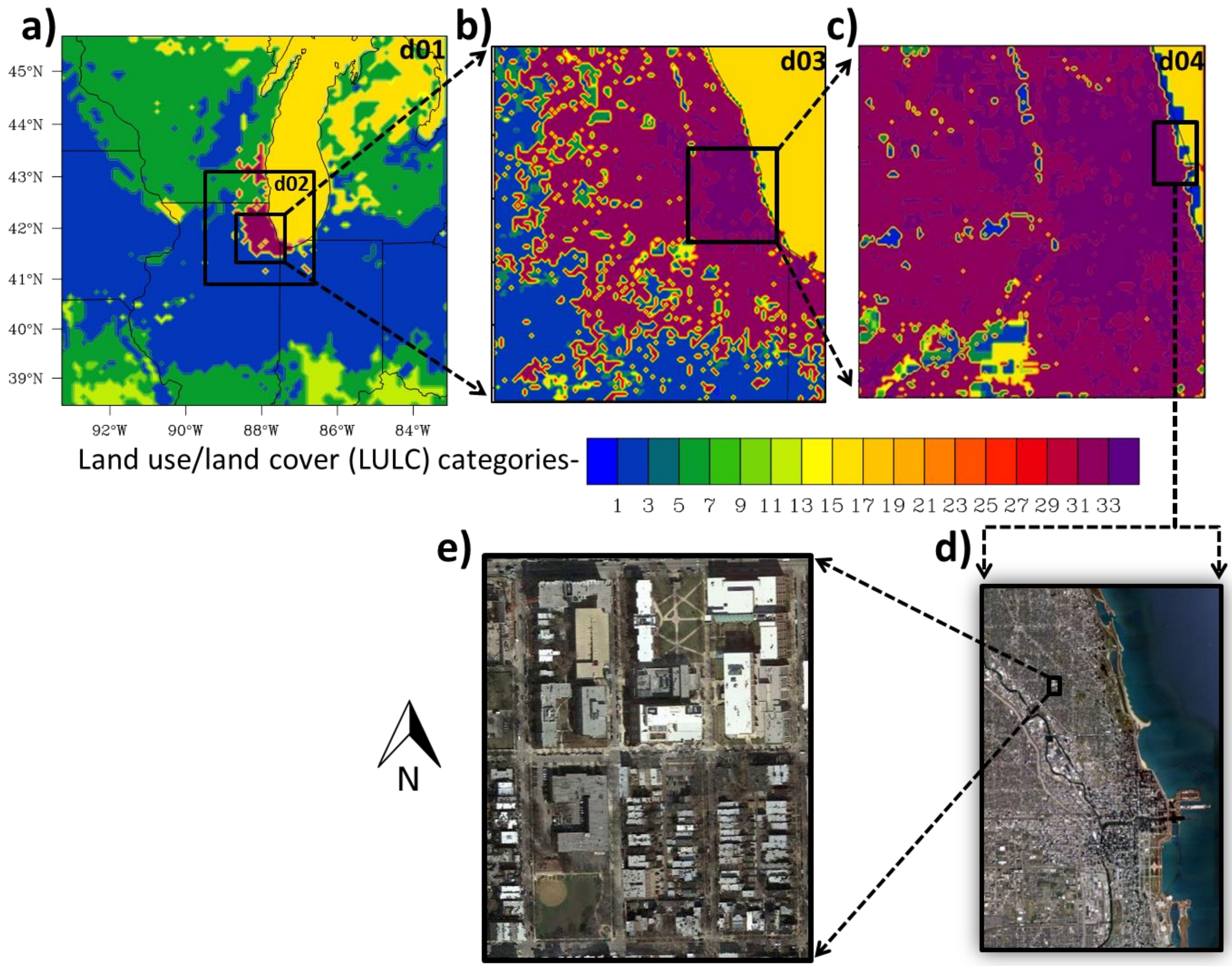
- 2.5 degrees → 9 km → 3 km → 1 km → 333 m → 2 m

Global
Community Atmospheric Model (CAM) of Climate System Model (CCSM5)

Mesoscale
Weather Research and Forecasting (WRF) model coupled with urban parameterization scheme

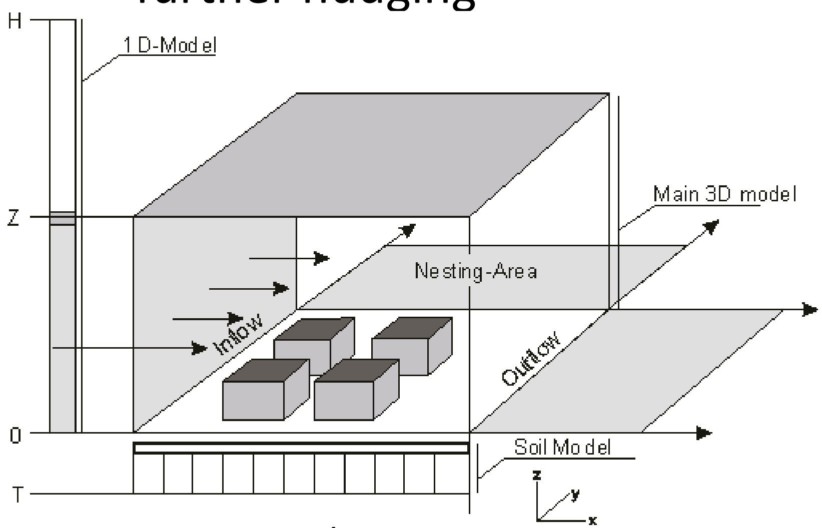
Micro-scale
ENVI-met

Multi-scale Modelling



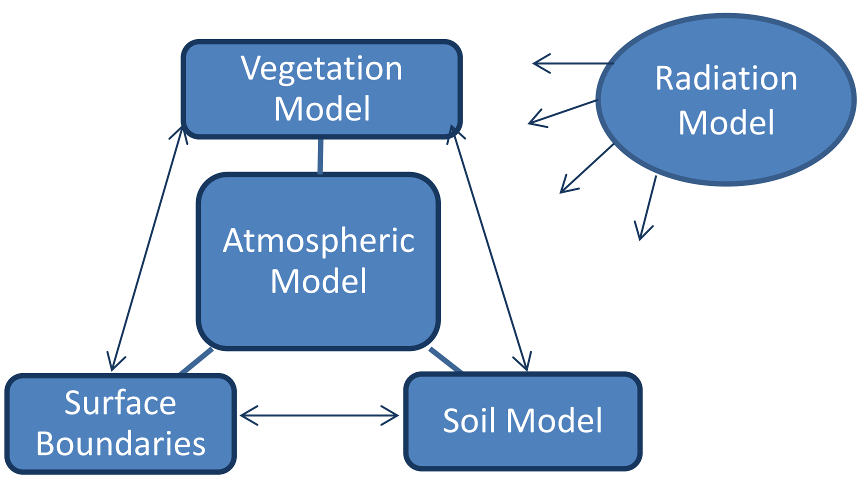
Micro-scale Model

- ENVI-met v3.1 developed by Michael Bruse (Bruse and Fleer 1998)
- 3D Reynolds Averaged Navier-Stokes model
  - Boussinesq approximation
  - k-ε 1.5 order turbulence closure scheme
- 1D model supplies lateral/upper boundary conditions for 3D model
  - Only initial conditions fed by user; thereafter marches forward in time without further nudging



www.envi-met.com

- Includes additional models:



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MODEL VALIDATION

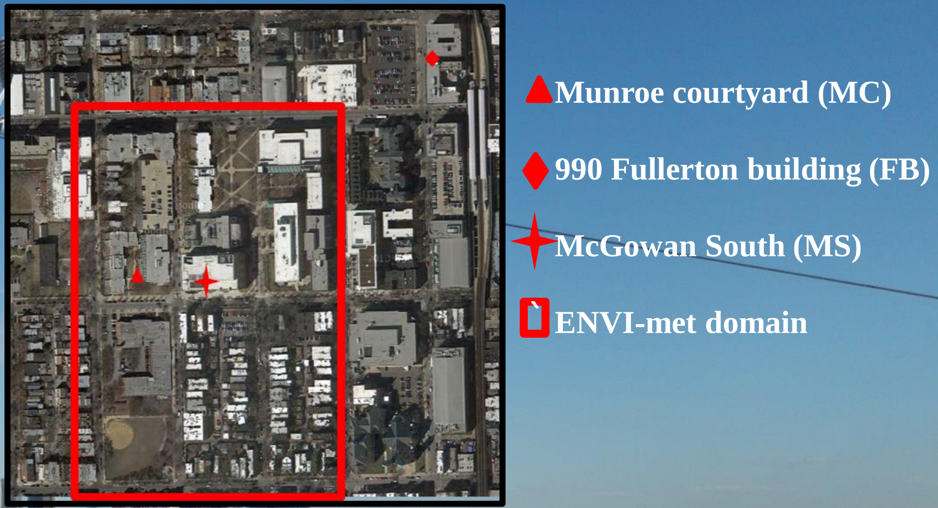
Mesoscale Model Performance

WRF performance statistics at 8 urban stations

Station identifier[a]	lat, lon (°N, °W)	2-m temp (°C)		10-m ws (m s^{-1})	
		RMSE	MAE	RMSE	MAE
MDW	41.7841, 87.7551	1.27	1.04	1.38	1.16
ORD	41.9875, 87.9319	1.78	1.45	1.22	0.99
AR820	41.9600, 87.7995	2.34	2.00	1.22	1.03
D6362	41.9483, 87.6586	1.36	1.06	1.33	1.05
D7813	41.8238, 87.8485	2.46	2.06	1.06	0.85
D8777	41.9333, 87.6725	1.25	1.02	1.53	1.07
E3114	41.8818, 87.6633	1.41	1.09	1.19	0.90
IL010	41.8325, 87.6949	1.53	1.21	1.57	0.85

Field Experiment

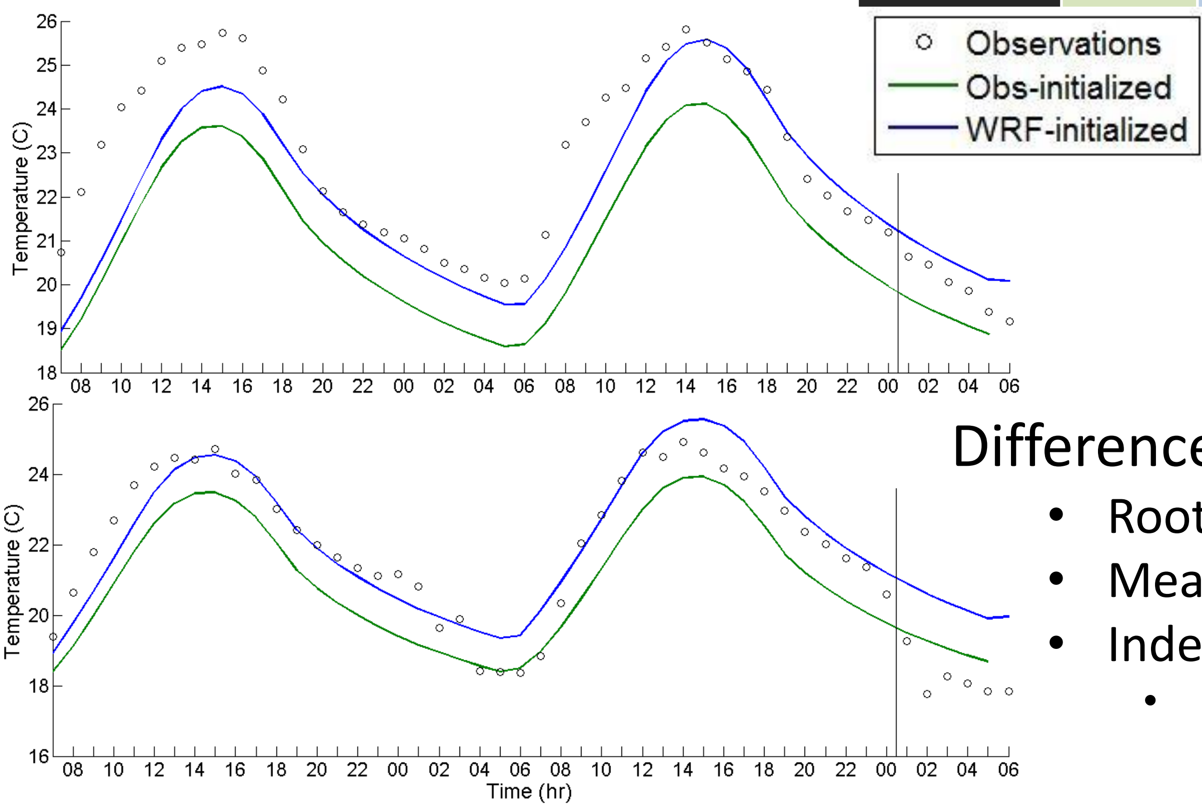
- Field campaign conducted July 24-August 21, 2013 at DePaul University
- Obtain reliable dataset for validation of ENVI-met in our model chain
- Pictured is one tower on McGowan South (MS) building's rooftop



Coupled Model Validation

- August 17-18, 2013
- Two sets of initial conditions

Station	RMSE (°C)		MAE (°C)		*d*	
	Obs.	*WRF*	*Obs.*	*WRF*	*Obs.*	*WRF*
MS1	1.94	1.15	1.83	0.86	.784	.909
MC1	1.20	0.65	1.04	0.53	.901	.971



Difference measures

- Root mean square error (RMSE)
- Mean average error (MAE)
- Index of agreement (*d*)
  - values approaching 1.0 = good model performance

CLIMATE-CHANGE APPLICATIONS

Climate-Change Applications

- CAM output averaged over years 2076 to 2081 fed into WRF
- Average lake-breeze days over entire month of August to get an average future August lake-breeze day
  - provides initial conditions to ENVI-met model
- Take ‘typical’ present-day August lake-breeze conditions as August 18, 2013
  - Based on statistical analysis of meteorological records
- ENVI-met can give finescale results for applications such as pedestrian comfort and building energy consumption

Lake Breeze

- Used criteria from Laird et al. (2001) to count lake breeze occurrences using WRF and observations at A , B, and C on August 15-19, 2013

		Observed lake breeze	
	Event	Lake breeze	No lake breeze
WRF-urban estimated lake breeze	Lake breeze	10	1
	No lake breeze	0	4

- 100% probability of detection; 20% probability of false detection; 0.07 false alarm rate

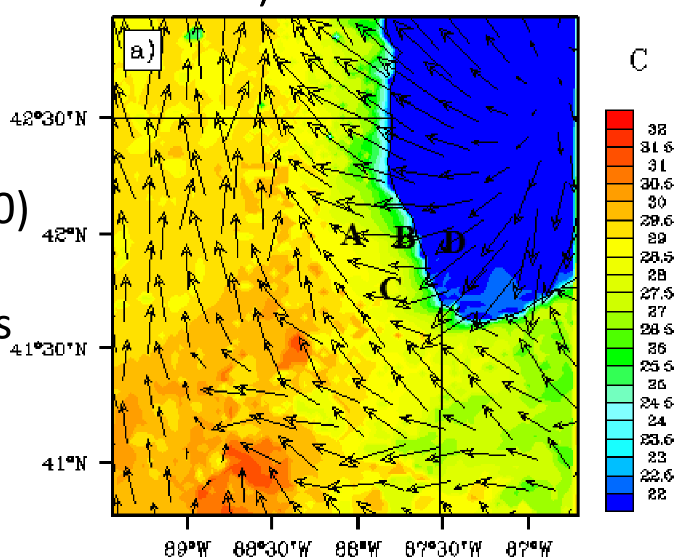
Daytime

(1400 – 1700)

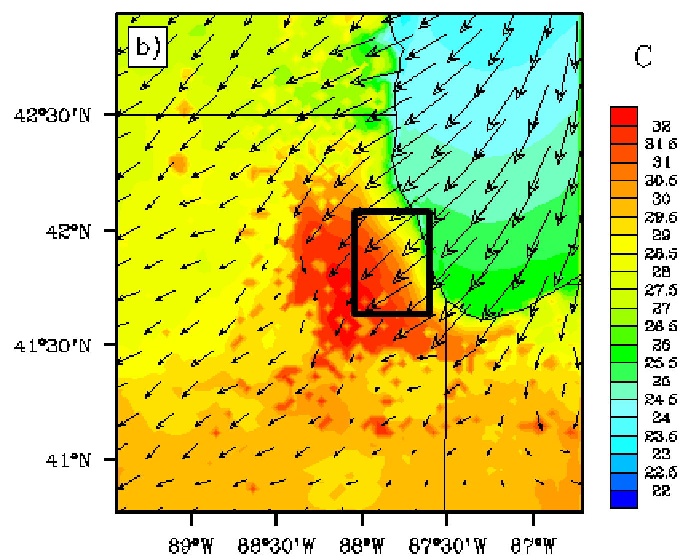
2-m Temp.

10-m Winds

a) Present



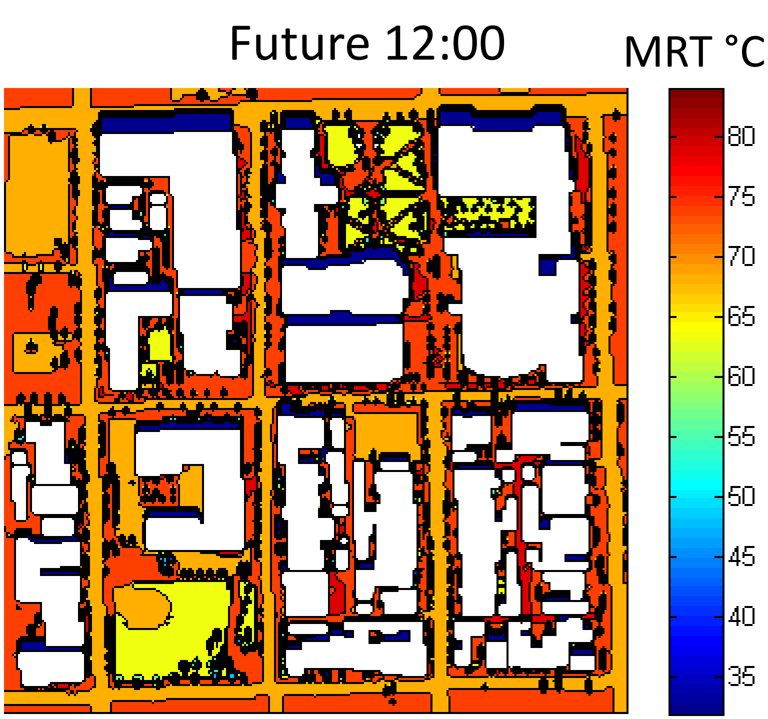
b) Future

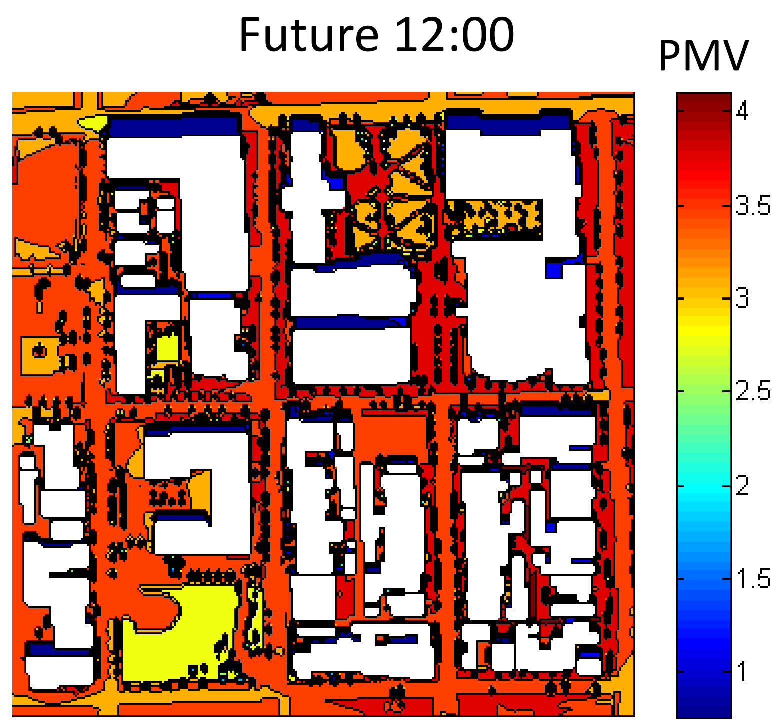


urban area 1.8 °C warmer than rural In future

Pedestrian Comfort

- For thermal comfort mean radiant temperature (MRT) is highly influential
- Use Predicted Mean Vote (PMV) as thermal comfort index (Fangers 1970, Jendritzky 1990) – depends on temperature, MRT, humidity, and wind speed but MRT clearly dominates
- On average, 92% of people have discomfort with future outdoor conditions





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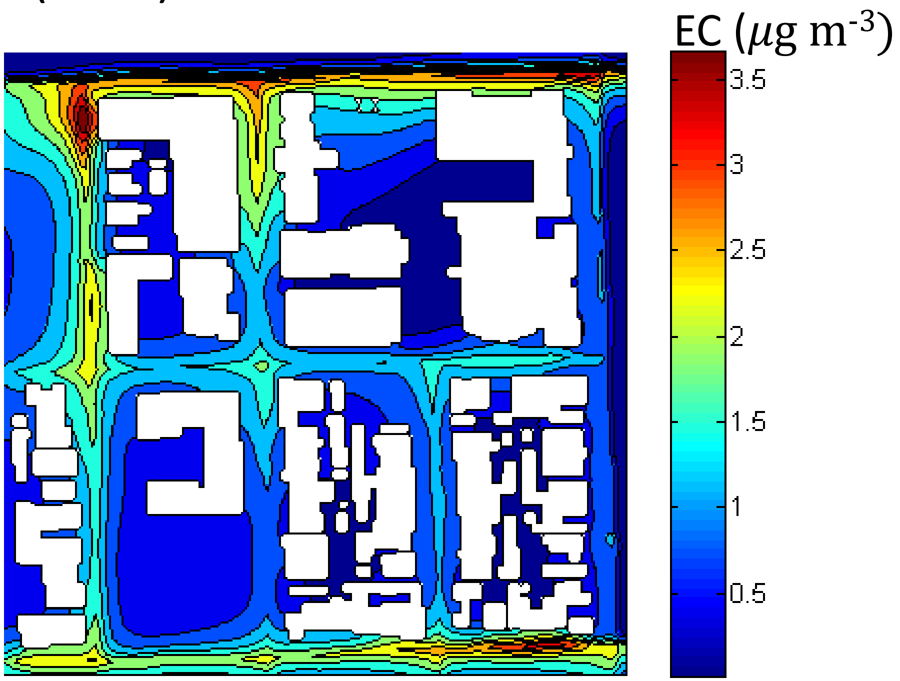
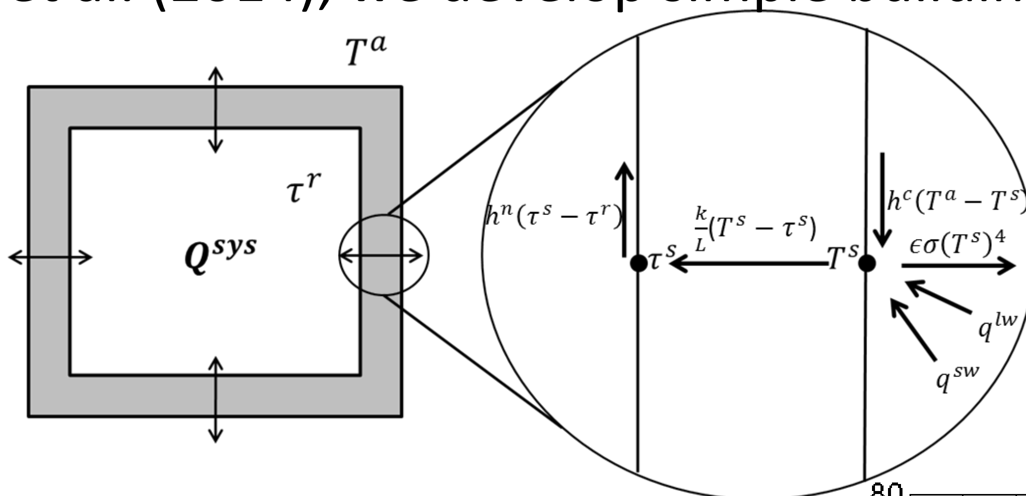
Pollutant Dispersion

- Pollution from traffic emissions also has major impact on pedestrian comfort
- Particle dispersion in ENVI-met (Bruse 2007)
  - ENVI-met uses standard application advection-diffusion equation
  - Accounts for particle deposition on vegetation and horizontal surfaces
  - Can create sources of particulate emission in domain
- We follow Vos et al. (2012) to simulate traffic emissions of elemental carbon (EC)

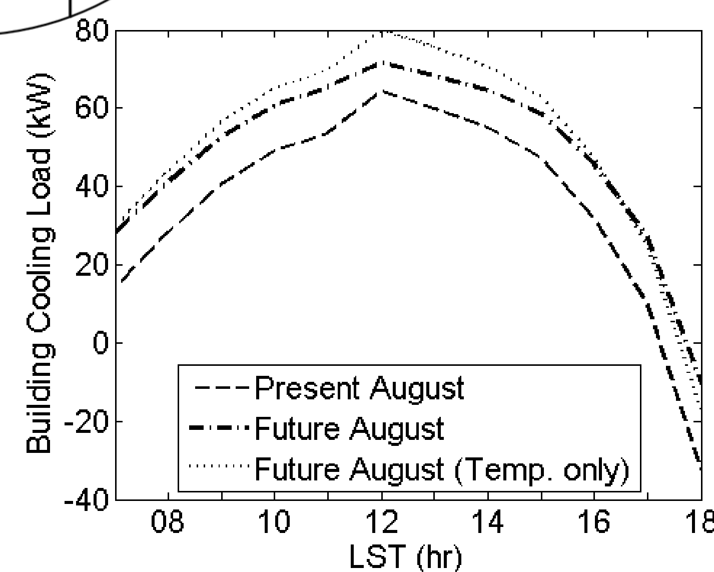


Building Energy

- In Conry et al. (2014), we develop simple building energy model



- Cooling load during daytime increases 26.0%
- Without slightly increased wind speed (only temperature change), cooling load increases 35.7%



CONCLUSIONS

Conclusions

- Multi-model chain utilizing dynamical downscaling developed as comprehensive tool for studying UHI and climate change
- Coupling mesoscale and microscale can improve performance at microscales
- Exacerbated UHI and air temperature outweigh slightly strengthened lake breeze, seriously threatening sustainability of Chicago

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