Understanding the Role Heat Island Control Could Have in Improving Air Quality

California Energy and Air Quality Conference
California Energy Commission – PIER-EA

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Haider Taha
Altostratus Inc.
(925) 228-1573
haider@altostratus.com – www.altostratus.com

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PRESENTATION TALKING POINTS

(and take-home messages)

- Urban heat islands (UHI): impacts, mitigation, and regulatory
- UHI PIER-EA project objectives
- Selected results from previous phases of project
- Development of new and meso-urban UHI modeling capabilities and needed data
- Mesoscale and meso-urban modeling applications: CA and Sacramento example
- SIP Voluntary Measure modeling for the Sacramento Metropolitan AQMD
- Future directions, research needs, and potential projects

Acknowledgements

California Energy Commission – PIER
Marla Mueller, Nicole Davis, Kelly Birkinshaw

URBAN HEAT ISLANDS (UHI)

Symptoms:

- Surface temperature + 10-20K
- Air temperature + 1-6K
- Velocity ± 2-5 m/s
- Mixing, Turbulence

Impacts on / exacerbation of:

- Cooling energy use
- Emissions (NOx, VOC, CO2, ..)
- Photochemical production of O3
- Heat waves
- Thunderstorms, precipitation, and heat pollution plumes
- Local impacts of GCC (heat waves, AQ, emissions, energy use)

Potential ramifications / regulatory:

Inaccurate accounting for impacts of urban meteorology and UHIs (especially under scenarios of future growth) on emissions and photochemistry can bias attainment demonstration

Current regulatory / SIP modeling is not sufficiently resolved within the UCL or urban areas in general, thus can underestimate urban effects. Corollary: potential benefits from UHI mitigation are not properly accounted for

Climate change will impact air-quality control; thus UHI mitigation can become a viable additional control strategy in the future (expected local impacts of GCC ~ magnitude of UHI) -- thus should be evaluated

UHI AND THE REGULATORY ENVIRONMENT

- Urbanization and land-use / cover changes (and associated changes in emissions and meteorology) have the potential to impact a region's attainment status – in the short term and under future climates
- UHI control can help maintain / improve air quality: national / international interest in incorporation of UHI mitigation into regulatory frameworks (direct / indirect, energy / atmospheric pathways)
- Cool roofs – California Title 24
- Urban forest – Sacramento Metropolitan AQMD (SMAQMD) UFFCA Project
- ARB: climate change early action: high-albedo materials (buildings, automotive cool paints' portion of the AB32 Early Action Plan)
- UHI Modeling Protocol submitted to EPA for commenting / approval for use in SIP modeling for SMAQMD UFFCA demonstration project: A potential template for use in future modeling efforts by other air districts / organizations

PIER UHI
PROJECT OBJECTIVES

- Evaluate impacts of UHI mitigation on energy, emissions, and air quality
- Develop and improve models and modeling frameworks; develop fine-resolution meso-urban UHI modeling capabilities
- Develop new techniques for surface morphology and canopy-layer characterizations, LULC characterization, and surface perturbation scenarios for use in fine-resolution models
- Apply mesoscale and fine-resolution meso-urban meteorological and photochemical modeling frameworks to California and evaluate the potential impacts of UHI control on ozone air quality at sub-meso scales; evaluate emission-reduction equivalents
- Develop models, data, implementation scenarios, modeling methodologies and initial results for consideration of UHI mitigation in SIP, e.g., SMAQMD urban forest, EPA OAQPS
- Provide guidelines for implementation

POTENTIAL PATHWAYS TO MITIGATE URBAN HEAT ISLANDS

- Albedo / effective albedo — note → (> 0.37 μm)
- Vegetation cover — note → (biogenic HC emissions)
- Anthropogenic heat flux
- Storage heat flux, thermal mass, materials properties
- Moisture and runoff
- Urban geometry

- Zero and low-emitters
- Water consumption
- Fire potential
- Maintenance

- Light-colored
- Reflective black or dark

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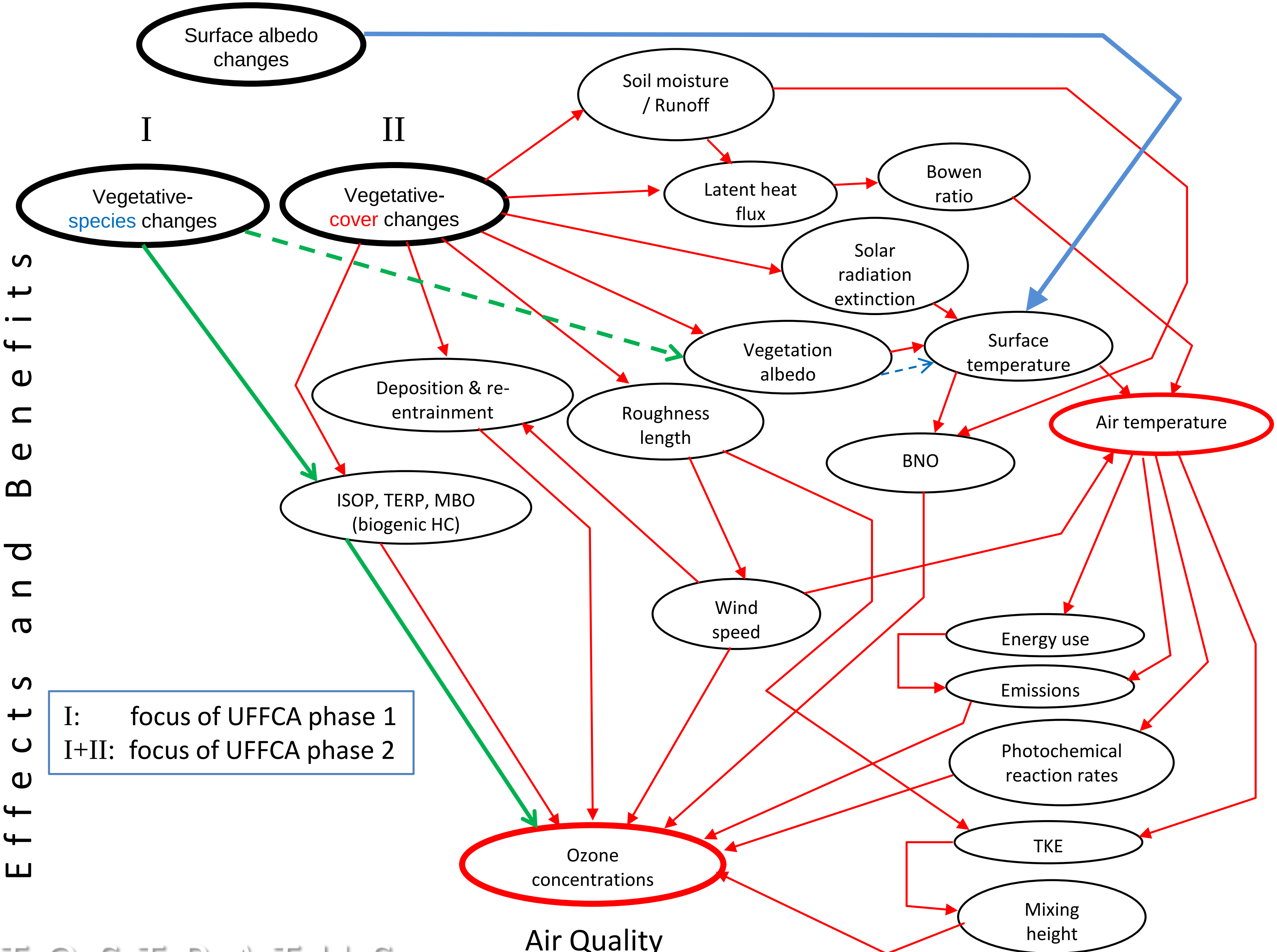
PHYSICAL PATHWAYS:
Effects and Benefits



I: focus of UFFCA phase 1
I+II: focus of UFFCA phase 2

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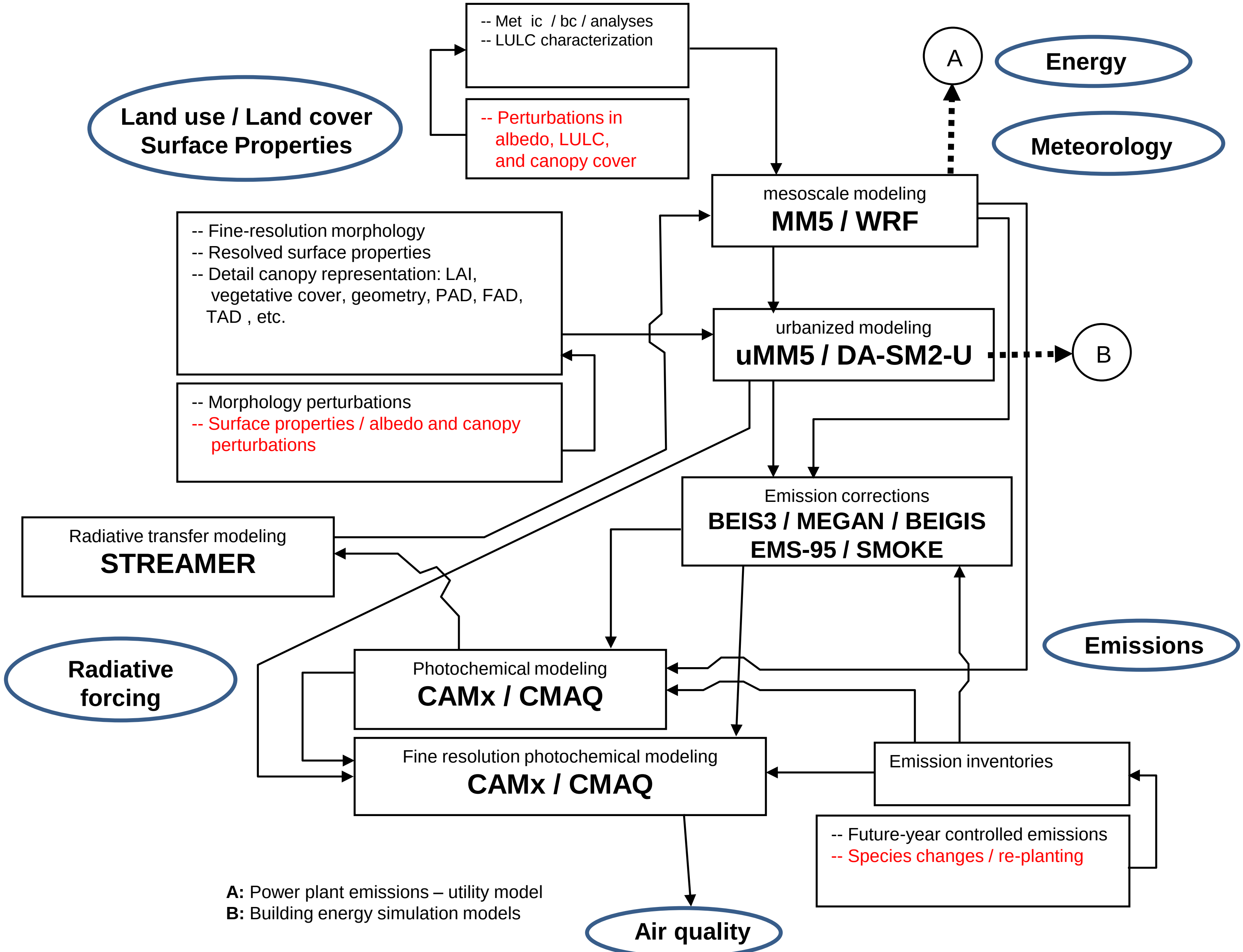
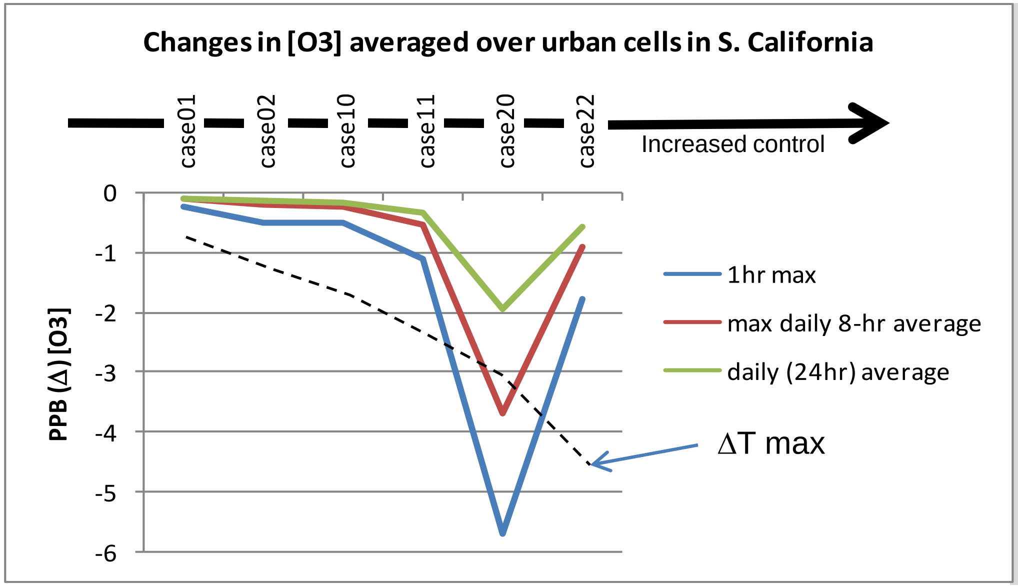
MODEL / DATA PATHWAYS



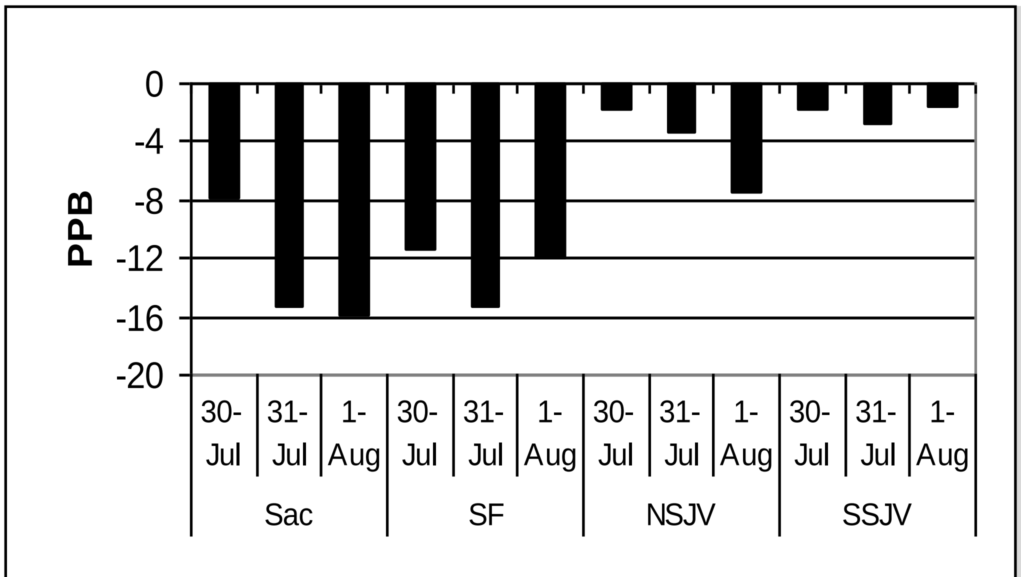
EXAMPLE MESOSCALE RESULTS



Southern California

Changes in O3 averaged over urban cells in Southern California: Simulated UHI control for August 5th. Note *threshold* effect

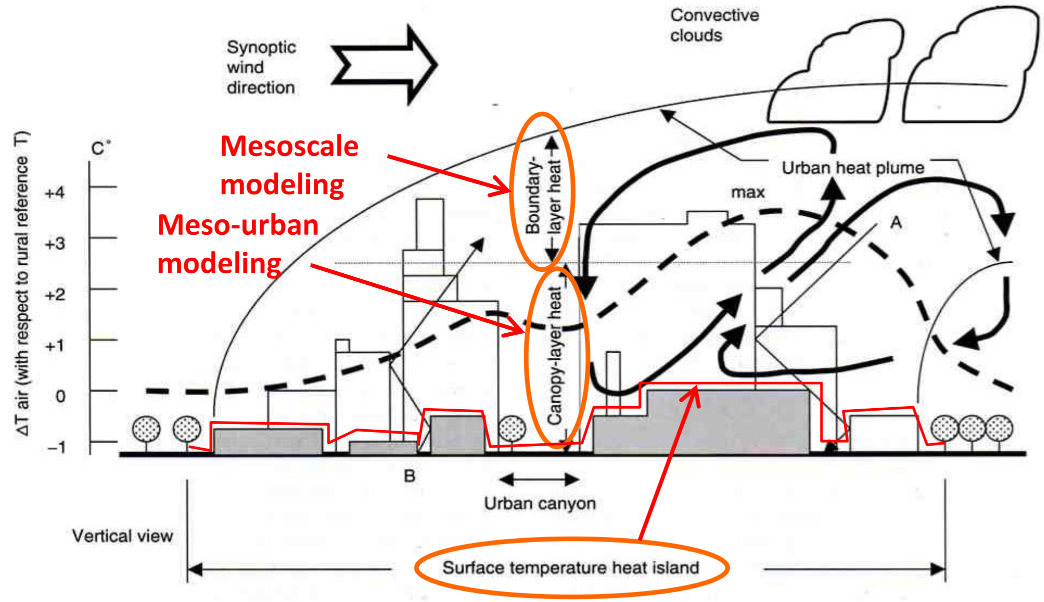
Case##
albedo ∊ 0,1,2
veg cover ∊ 0,1,2
0: none
1: moderate
2: high



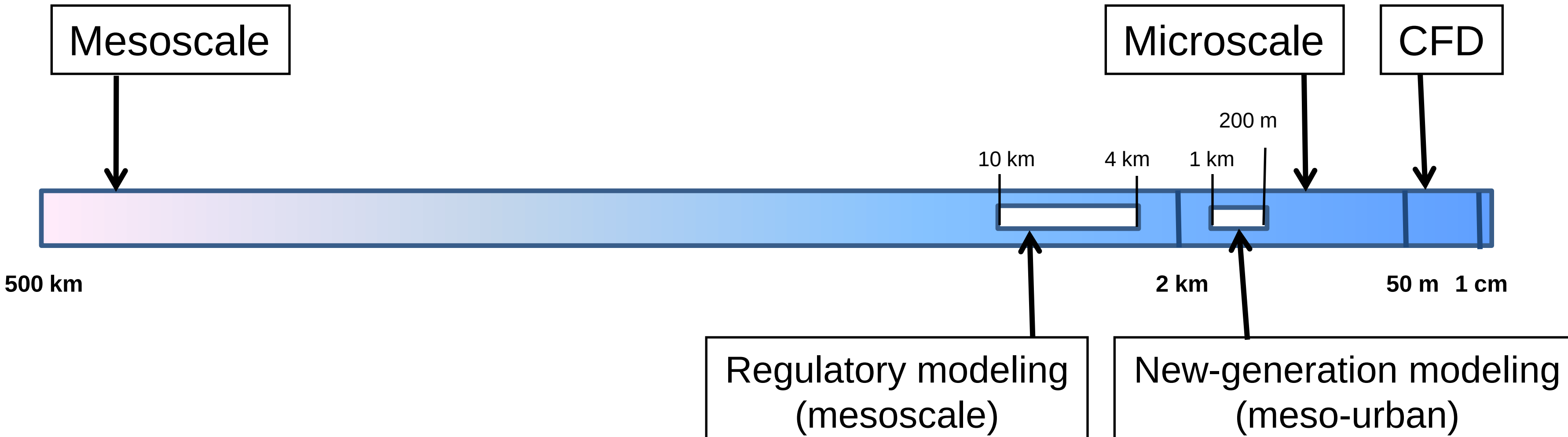
Central California

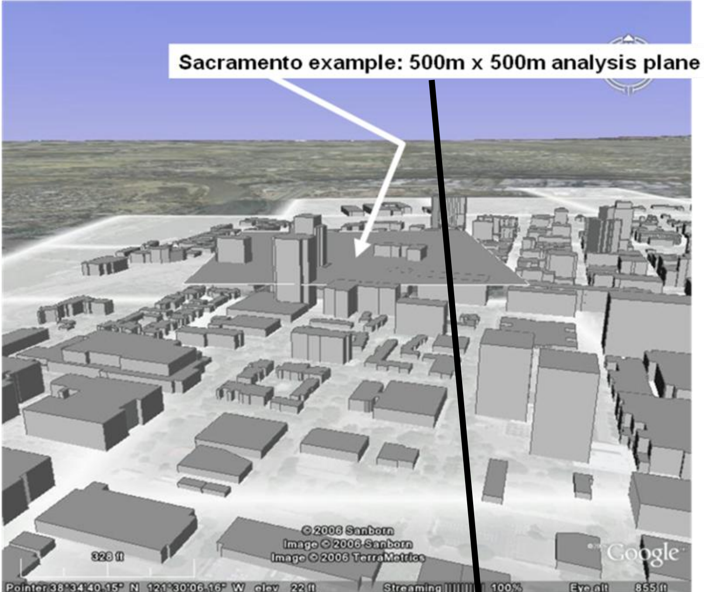
UHI control (increased urban albedo) impacts on regional **1-hour** O3 peaks in four Central California regions

Fine-resolution modeling of heat island control



Source: Taha 2004.
Encyclopedia of Energy, Elsevier





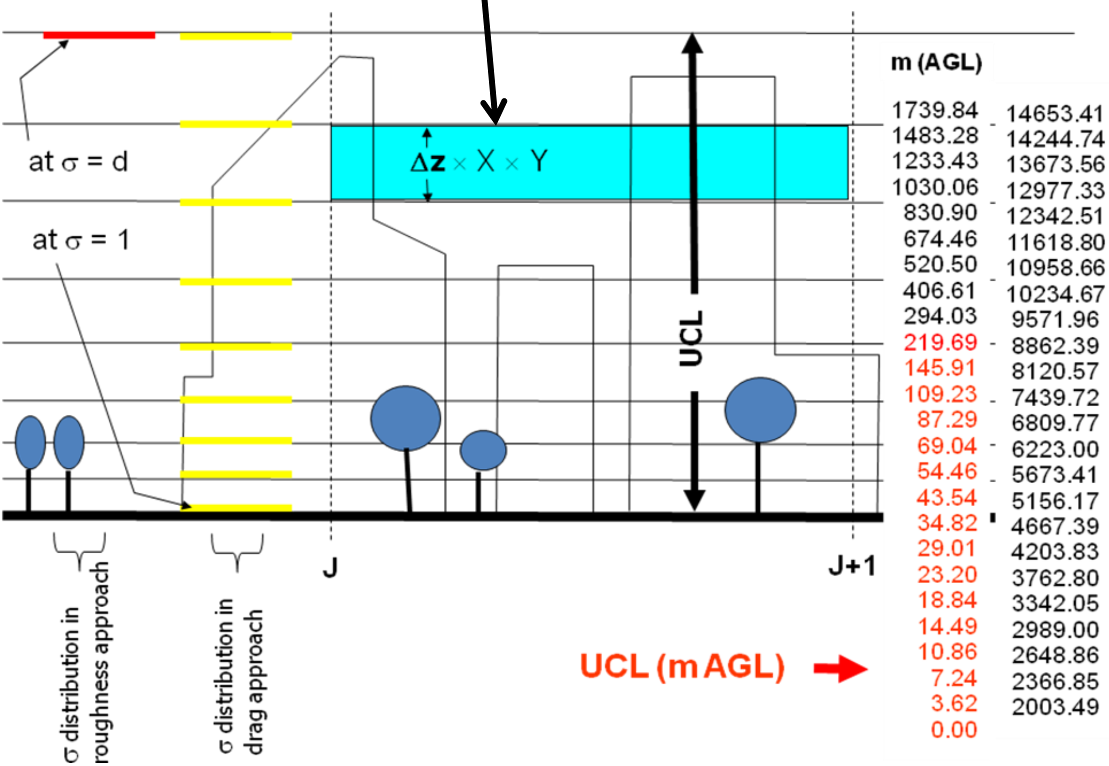
Meso-urban modeling: uMM5

$$\frac{\partial \rho u_i}{\partial t} = F_{g(ui)} + \underbrace{F_{ui}^{j}}_{1} + \underbrace{\sum_j D_{ui}^{j}}_{2}$$

$$\frac{\partial \rho \theta_L}{\partial t} = F_{g(\theta L)} + \underbrace{H_j}_{3} + \underbrace{Q_f}_{4}$$

$$\frac{\partial \rho q}{\partial t} = F_{g(q)} + \underbrace{S_j}_{5}$$

$$\frac{\partial E}{\partial t} = \frac{\partial u_i E}{\partial x_i} + \left\{ k_m \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right] S_{air} + \underbrace{F_E^{bui}}_{6} \right\} + \left\{ \frac{g}{\theta_v} \langle w \theta_v \rangle + \underbrace{H_E}_{7} \right\} - \frac{1}{\rho} \frac{\partial \left(\rho \langle wE \rangle \right)}{\partial z} - \varepsilon + \underbrace{\sum_j w_E^{j}}_{8} - \underbrace{\sum_j D_E^{j}}_{9}$$



+ Urban geometry / effective albedo / radiation trapping

+ Urban soil model (SM2-U)

Source: Taha 2008. *Boundary-Layer Meteorology*

uMM5 morphology input and region-specific land-use and land-cover classification

Useful spatial resolution: ΔX, ΔY ~ 250m; ΔZ ~ 1-2m

Land-use fraction (e.g., Level-II 38-USGS, or new system)
Land-cover fraction (paved)
Land-cover fraction (roof)
Land-cover fraction (vegetation)
Land-cover fraction (water)
Building height-to-width ratio
Building wall-to-plan ratio
Connected impervious area
Mean orientation of streets
Mean building height
Vegetation mean height
Zo and Zd (grid level, surface-specific)
Building frontal area density (**multi-directional**) **(ΔZ)**
Building top (roof) area density **(ΔZ)**
Building plan area density **(ΔZ)**
Vegetation frontal area density (**multi-directional**) **(ΔZ)**
Vegetation plan area density **(ΔZ)**
Vegetation top area density **(ΔZ)**
Plan-area weighted mean building height
Sky-view factor **(ΔZ)**

- 11 Residential
  - 111 High-density
    - 1111 Detached
      - 11111 Single-Family
      - 11112 Multi-Family
    - 1112 Attached
      - 11121 Single-Family
      - 11122 Multi-Family
  - 112 Low-density
    - 1121 Detached
      - 11211 Single-Family
      - 11212 Multi-Family
    - 1122 Attached
      - 11221 Single-Family
      - 11222 Multi-Family
  - 113 High-rise/multi-family
  - 114 Condominiums
  - 115 Mixed residential (single/multi – attached/detached)
  - 116 High-density, mobile homes/parks
- 12 Commercial
  - 121 Low-rise commercial building; low-rise malls and strip malls
  - 122 High-rise commercial; high-rise offices
- 13 Industrial
- 14 Transportation and utility, Airports, Highways
- 15 Mixed commercial and industrial
- 16 Mixed urban
  - 161 Mixed commercial and residential
  - 162 Mixed residential and transportation (highways)
  - 163 Mixed green/open spaces and transportation (highways)
  - 164 Mixed residential and recreation
  - 165 Mixed residential and high-rise commercial
- 17 Other urban
- 18 Open space and/or recreation
- 19 Services
- 20 Downtown core
- 21 Urban high-rise
- 22 Academic and educational
- 23 Health services and hospitals
- 24 Sports
- 25 Other facilities, military, storage
- 31 Green / open areas / gold courses / vineyards and hills
- 99 Water, beaches, channels

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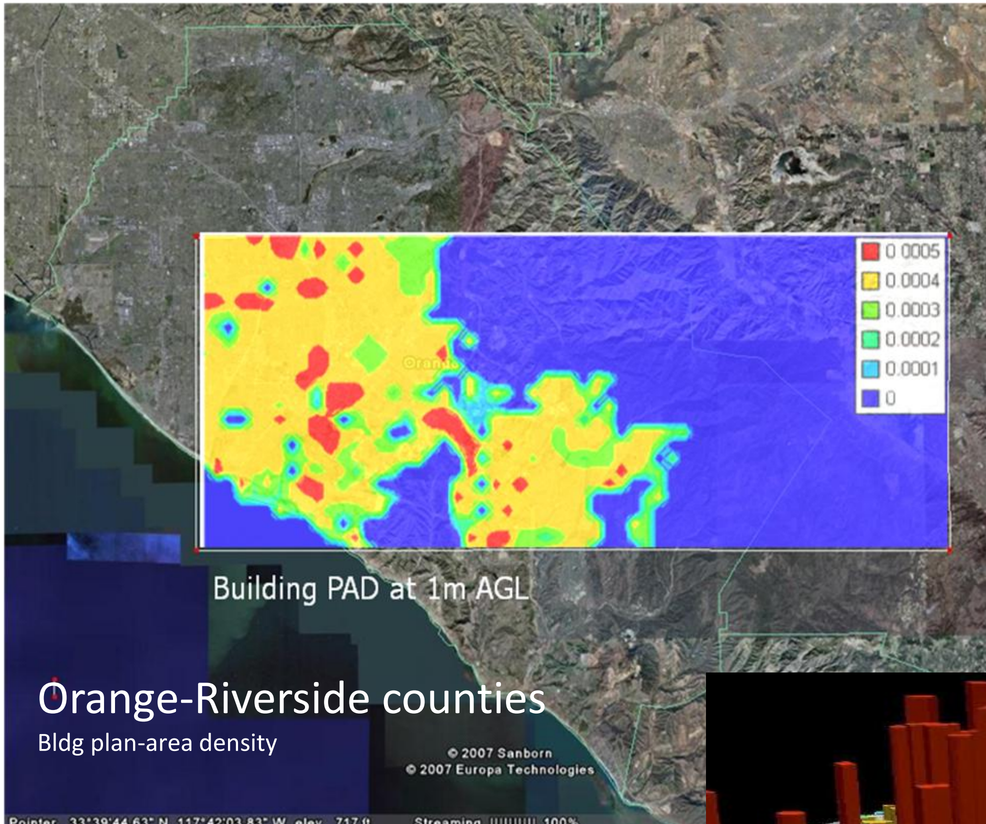
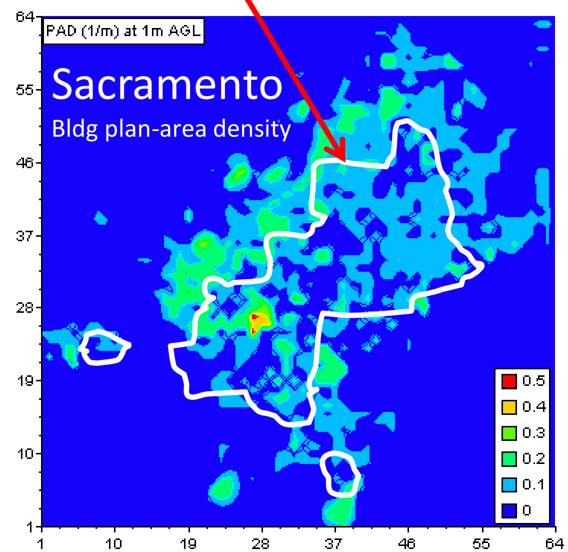
Improved urban regional / surface and morphological characterization



Sacramento default in models (MM5)



Development of fine-resolution 3-D urban canopy characterization for input to meso-urban models

Source: Taha (2007)

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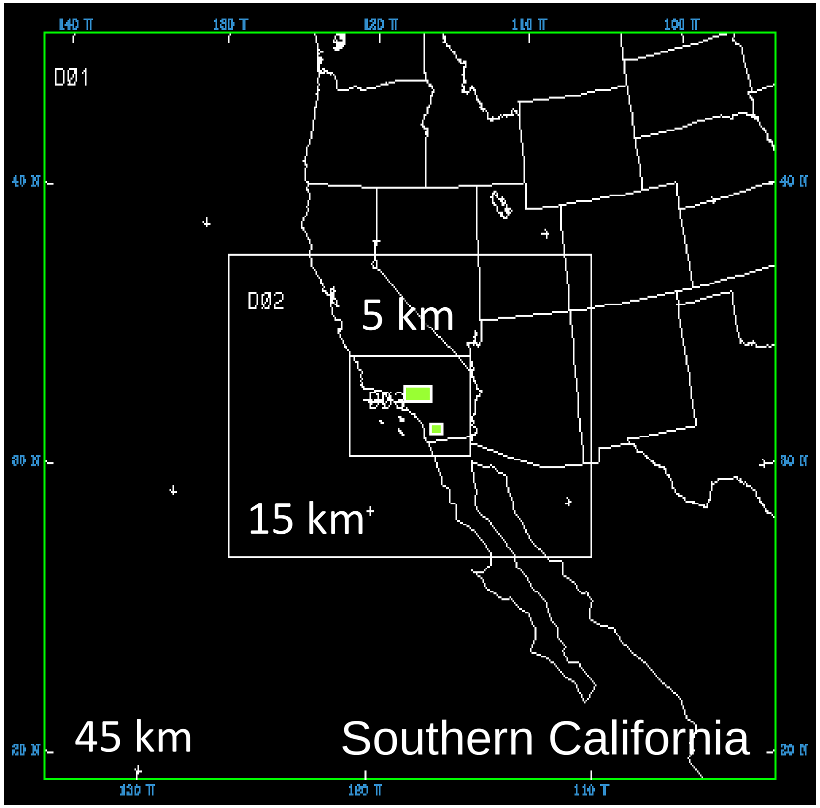
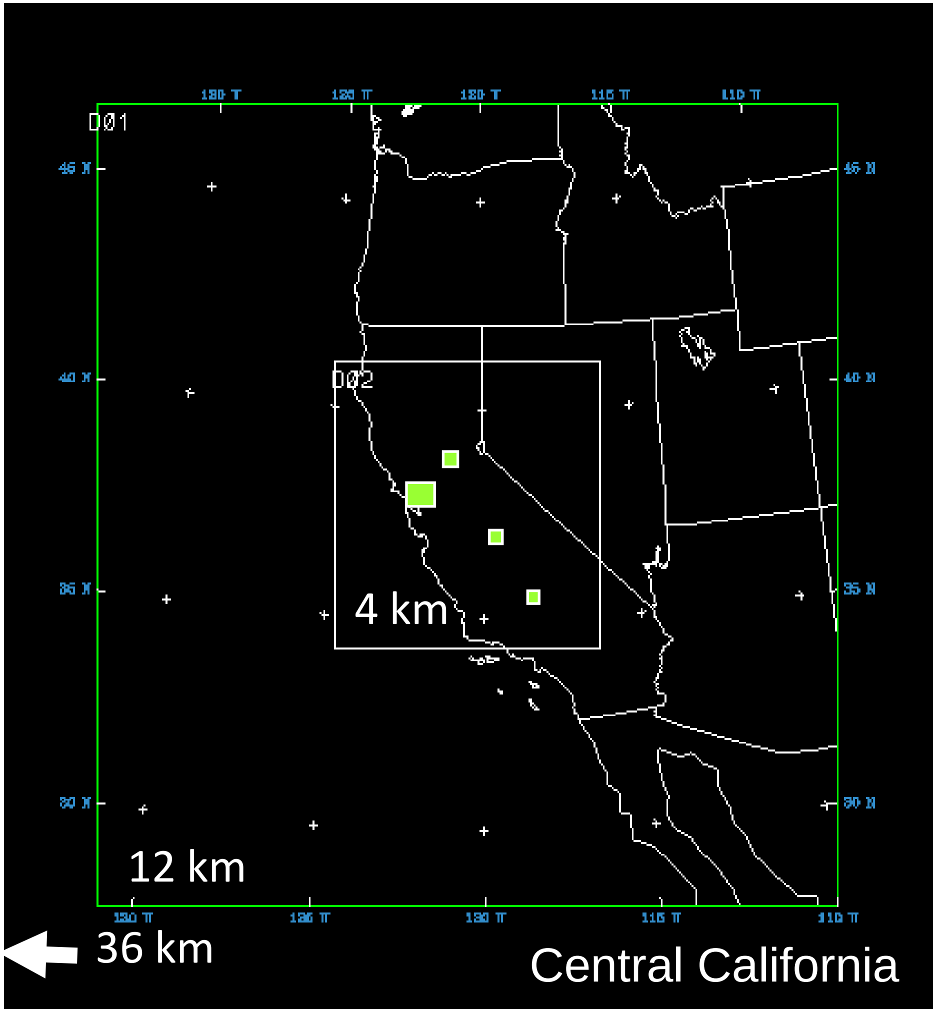
Use of uMM5 in research and regulatory modeling

- uMM5 / DA-SM2-U: used in NY and TX modeling
- uMM5 further developed in CEC PIER project and applied to CA
- EPA supports use of uMM5 in SIP modeling for the SMAQMD's UFFCA demonstration project
- uMM5 urban parameterizations now being ported to WRF (uWRF)
- uMM5 / DA-SM2-U now a component in NUDAPT (EPA's national urban database and modeling portal tool) for urban meteorological modeling

APPLICATIONS

California example

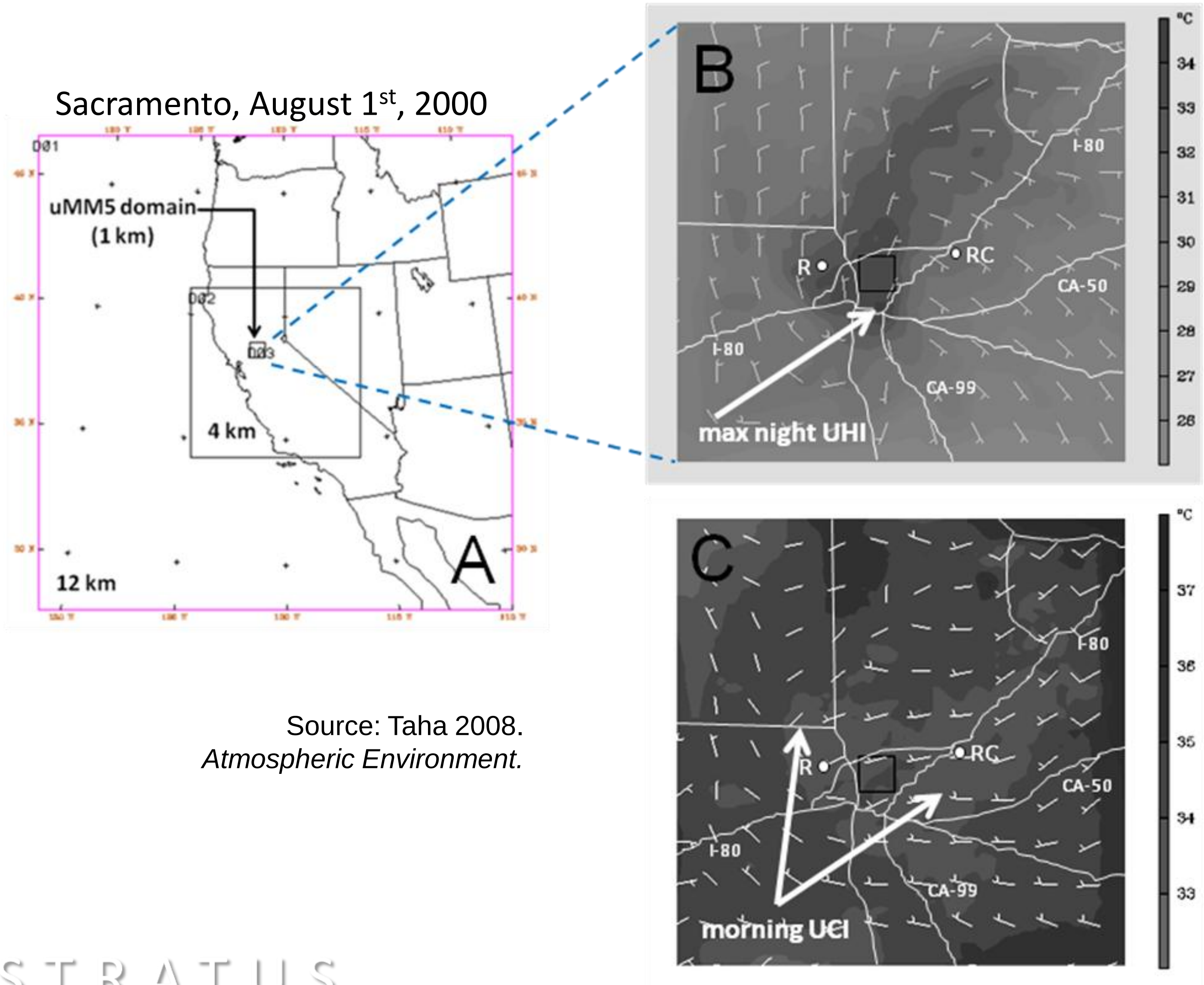




■ Mesoscale (O~4km+) modeling domains
■ Meso-urban (O~1km) modeling domains

Meso-urban modeling and fine-resolution meteorological features: Base-case simulation results: heat island, cool island, flow convergence

Sacramento, August 1st, 2000



Source: Taha 2008. *Atmospheric Environment.*

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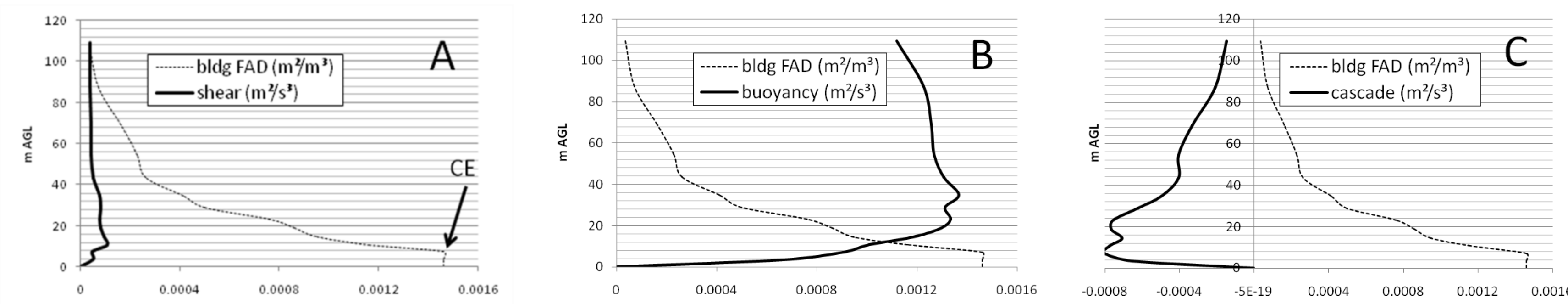
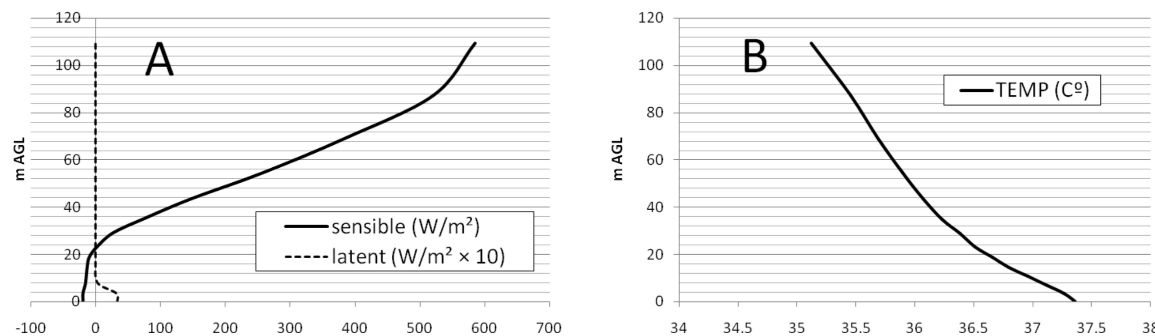
Meso-urban modeling and fine-resolution meteorological features: Base-case simulation results: TKE components, temperature, heat flux



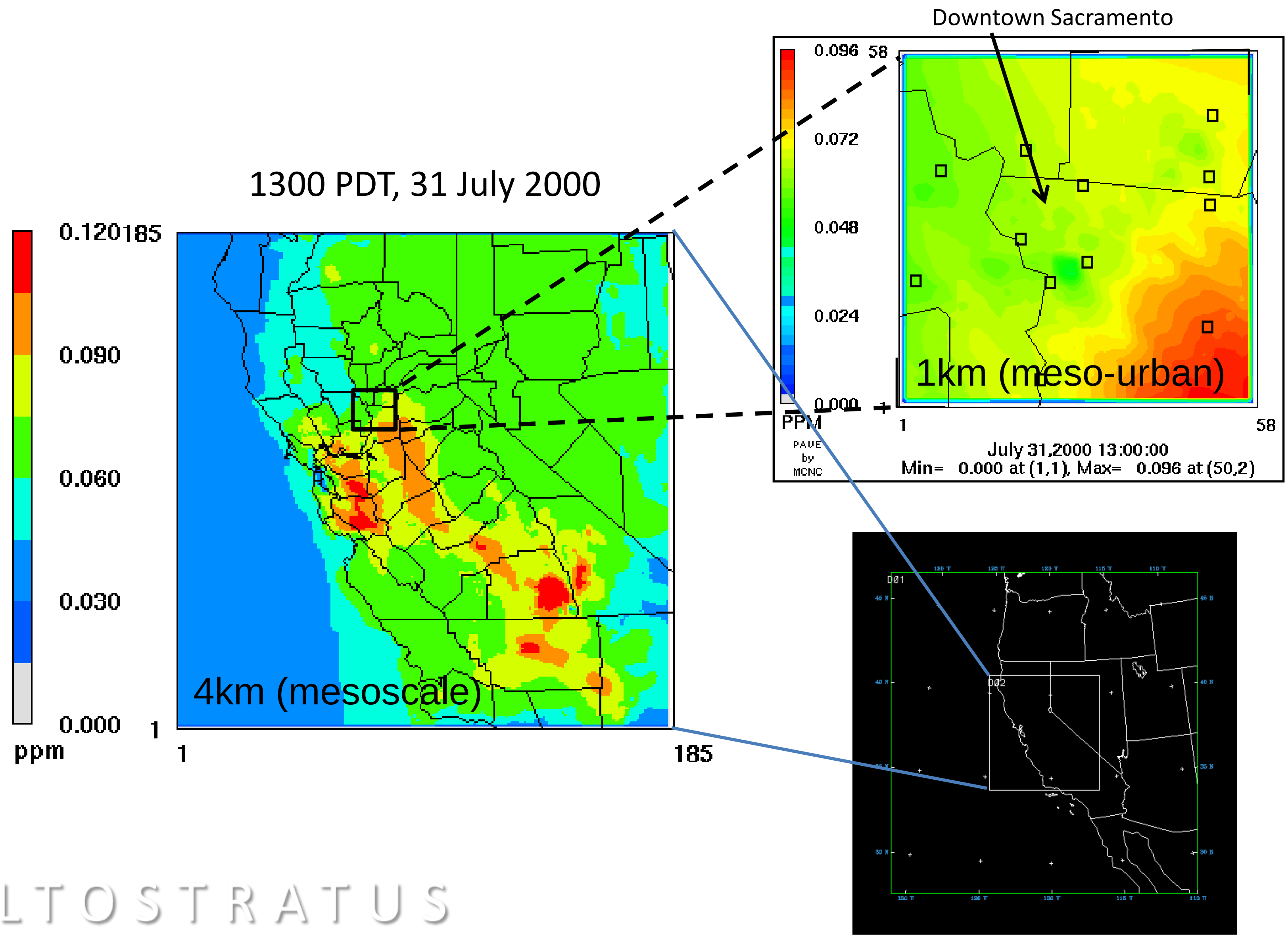
Selected TKE budget components (m^2s^{-3}) for a location in Downtown Sacramento. Also shown is building FAD (m^2m^{-3}).



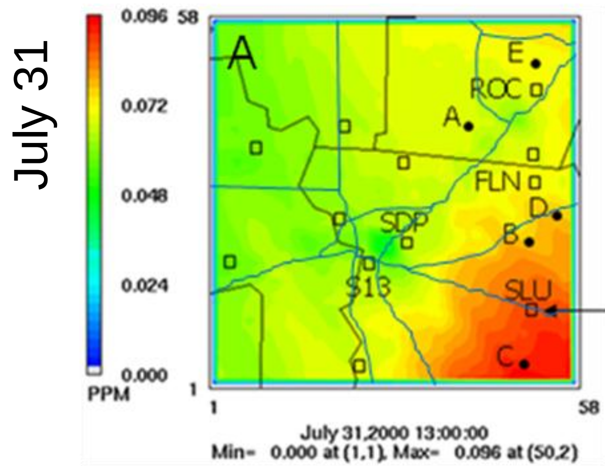
Sensible / latent heat flux (W m^{-2}) and air temperature (C^o) at a location in uMM5 domain / Downtown Sacramento

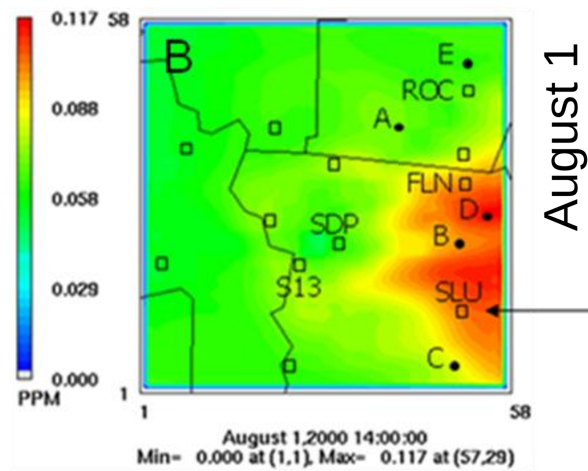
Source: Taha 2008.
Atmospheric Environment

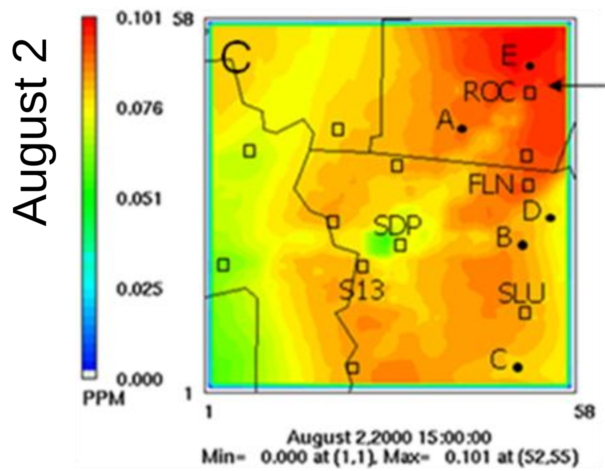
Meso-urban / fine-resolution photochemical modeling:
Base-case ozone, central CA and Sacramento



Meso-urban / fine-resolution photochemical modeling:
Base-case simulation results for Central CA and Sacramento





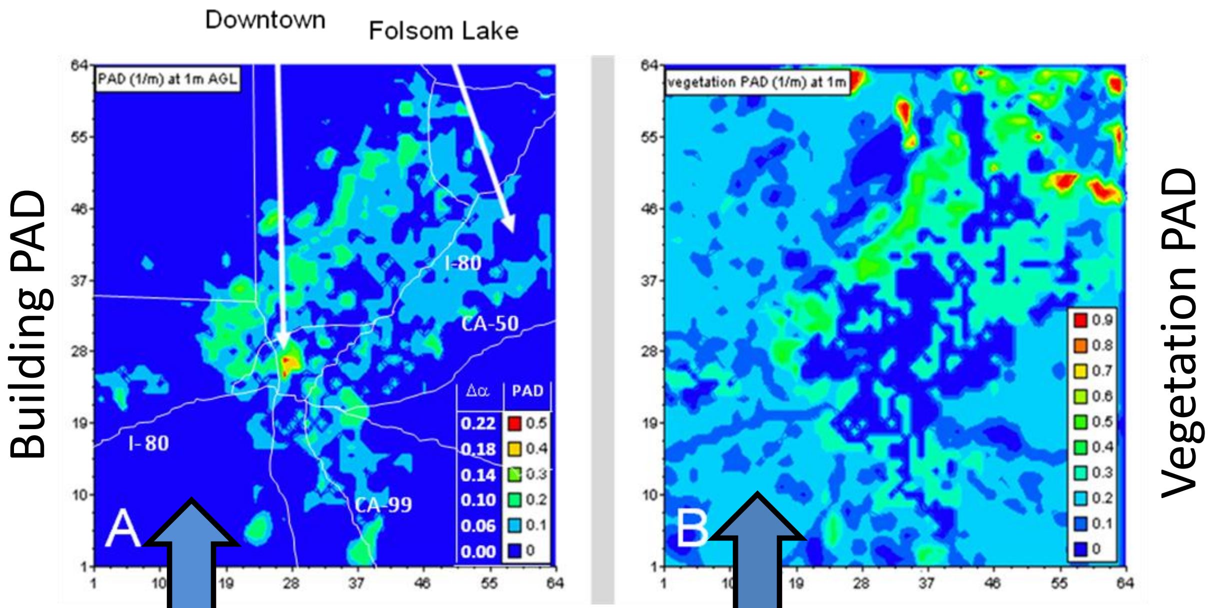


PAIRED			UNPAIRED		
OBS	SIM	PA	OBS	SIM	UA
100	88	0.88	100	96	0.96
133	108	0.81	133	117	0.88
110	97	0.88	121	101	0.83

Meso-urban meteorological and photochemical simulations : model performance

Source: Taha 2008.
Atmospheric Environment

Development of UHI control scenarios



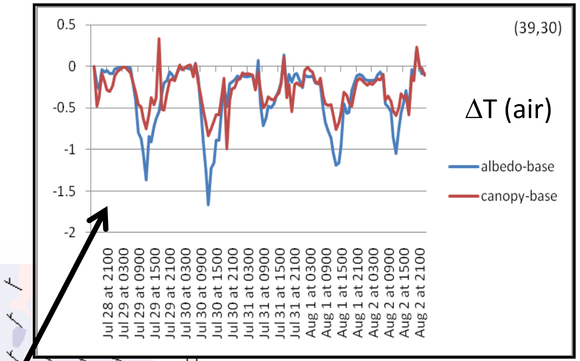
Albedo-increase basis

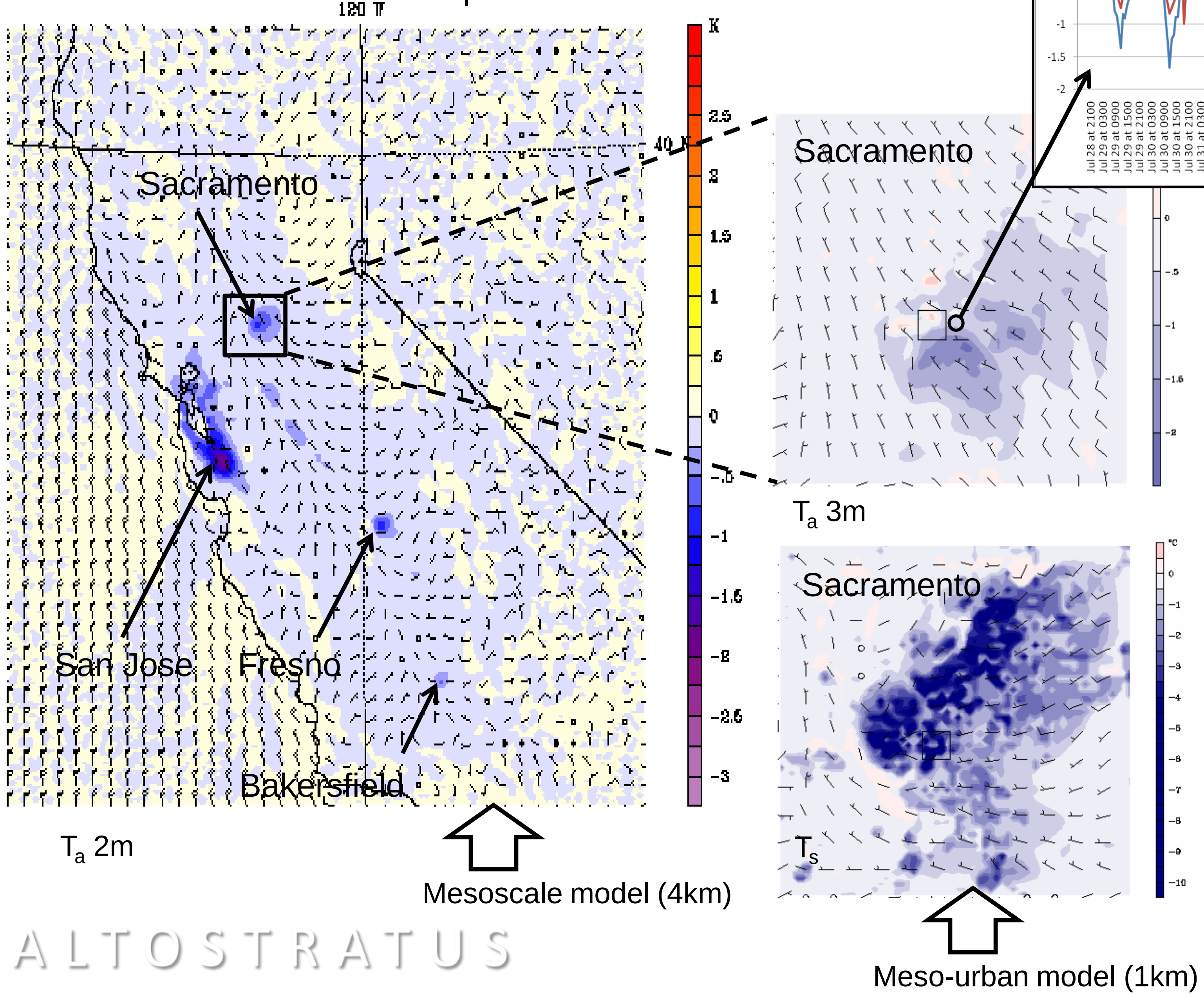
LULC	Specification of surface-specific albedo					
	Roof		Wall		Paved	
	Δα	New α	Δα	New α	Δα	New α
Residential	0.45	0.55	0.15	**0.40**	0.22	0.30
Commercial/Services	0.55	0.65	0.15	**0.40**	0.27	0.35
Industrial	0.55	0.65	0.20	**0.45**	0.27	0.35
Transportation/Communication	0.25	0.35	0.10	0.35	0.20	0.28
Industrial and commercial	0.55	0.65	0.20	**0.45**	0.27	0.35
Mixed urban or built up	0.45	0.55	0.15	**0.40**	0.22	0.30
Other urban or built up	0.45	0.55	0.15	**0.40**	0.22	0.30

Vegetation-increase basis

LULC		Typical base vegetative cover	Change for scenarios 01 and 11	Change for scenarios 02 and 22
Urban categories				
11	Residential	10%	9%	18%
12	Commercial/Services	12%	9%	18%
13	Industrial	5%	4%	8%
14	Transportation/Communication	3%	2%	4%
15	Industrial and commercial	7%	6%	12%
16	Mixed urban or built up	10%	5.5%	11%
17	Other urban or built up	7%	5.5%	11%

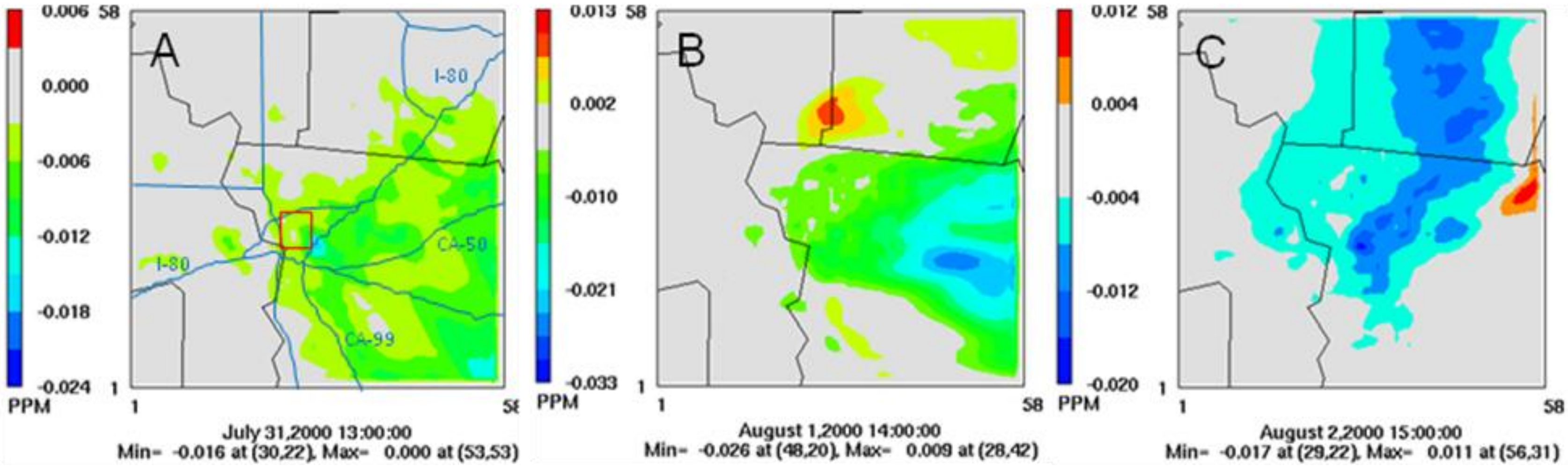
Meteorological impacts of increased urban albedo: Sacramento simulation example





A L T O S T R A T U S

Impacts of increased urban albedo on peak $[O_3]$: Sacramento example



July 31 | August 1 | August 2

Base-case peak (simulated)				Δ [O3] (ppb) at location of peak	
		Time of peak (LST)	Location of peak (see previous figure)	At time of peak	Max Δ [O3] at any time
	Peak (ppb)			Albedo - basecase	Albedo - basecase
July 29	103	1500	A	-8.7	-8.7 (at1500)
July 30	113	1500	B	-10.9	-11.1 (at 1600)
July 31	96	1300	C	-8.1	-10.6 (at 1200)
August 1	117	1400	D	-22.2	-22.2 (at 1400)
August 2	101	1500	E	-6.7	-9.2 (at 1600)

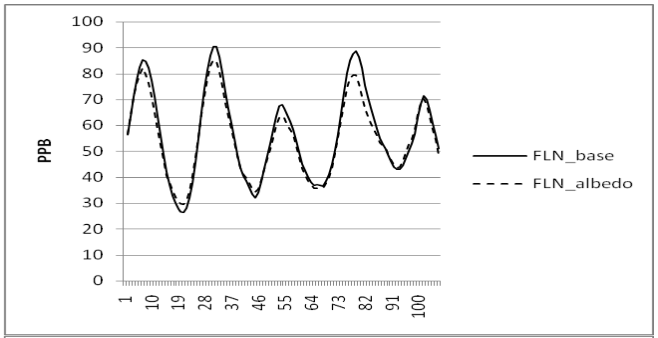
Changes in [O3] at time of base-case peak on each day of episode in the Sacramento **uMM5 domain** (resulting from increased urban albedo), corresponding to a decrease of up to 2-3 C in air temperature. Except for large localized decreases (or increases, e.g., on 1 August), average reductions affect large areas

Source: Taha 2008.
Atmospheric Environment

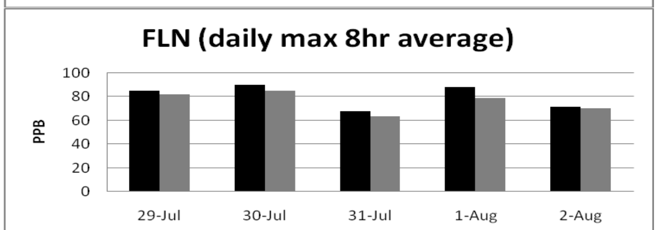
Potential air-quality improvements from increased urban albedo

8-hour average

A

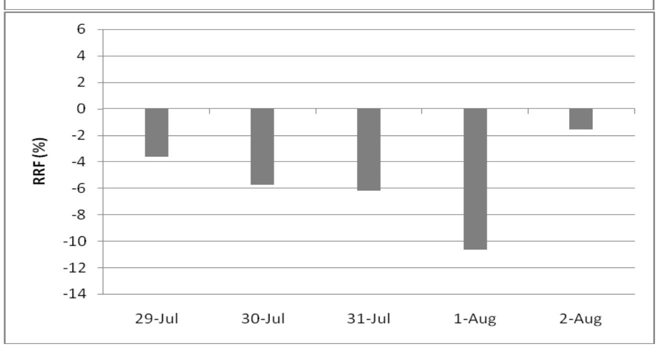


B

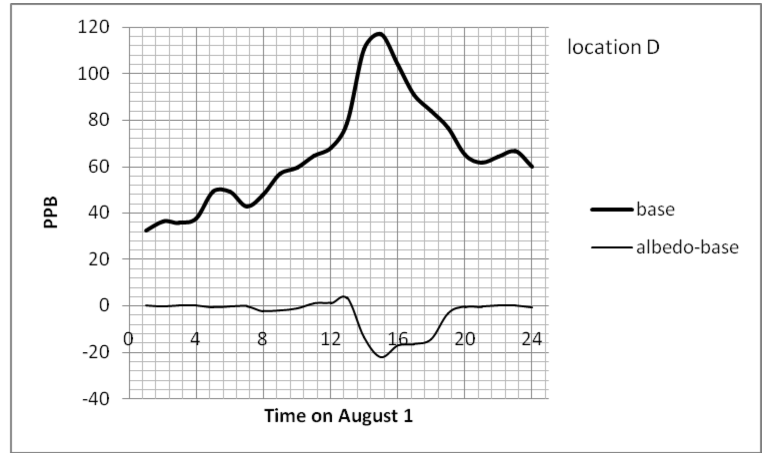


	29-Jul	30-Jul	31-Jul	1-Aug	2-Aug
base	85.3	90.3	67.9	88.5	71.3
albedo	82.2	85.1	63.7	79.1	70.2

C



1-hour average



August 1st, simulated ozone at a location in Sacramento (top of graph) and changes resulting from increased albedo (bottom of graph)

A: Simulated 8-hour average for base and high-albedo scenarios at Folsom-Natoma (FLN); **B:** simulated daily maximum 8-hour average ozone (at FLN); and **C:** reduction (%) in daily 8-hr maximum as RRF resulting from increased albedo.

Source: Taha 2008. *Atmospheric Environment*

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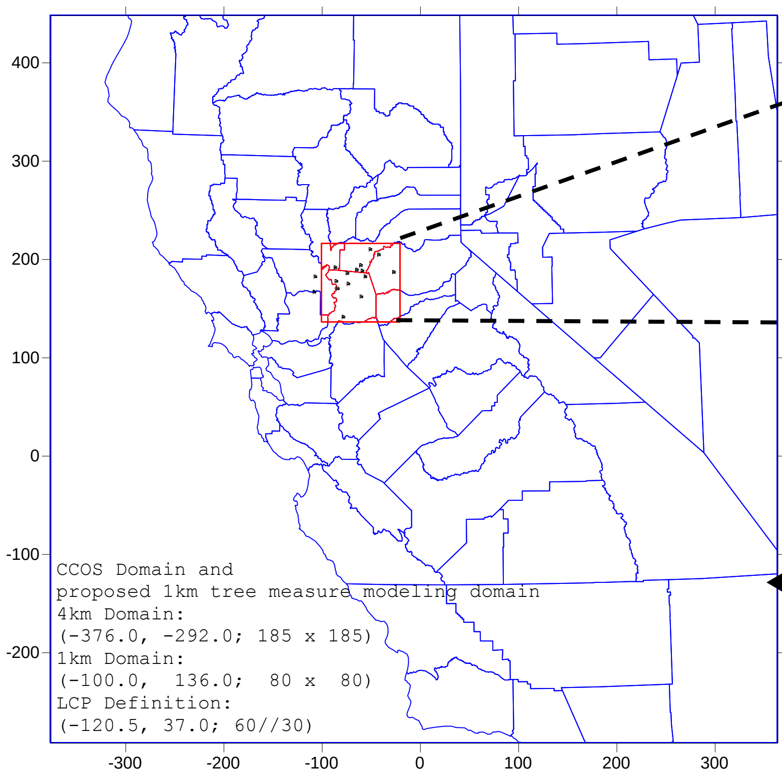
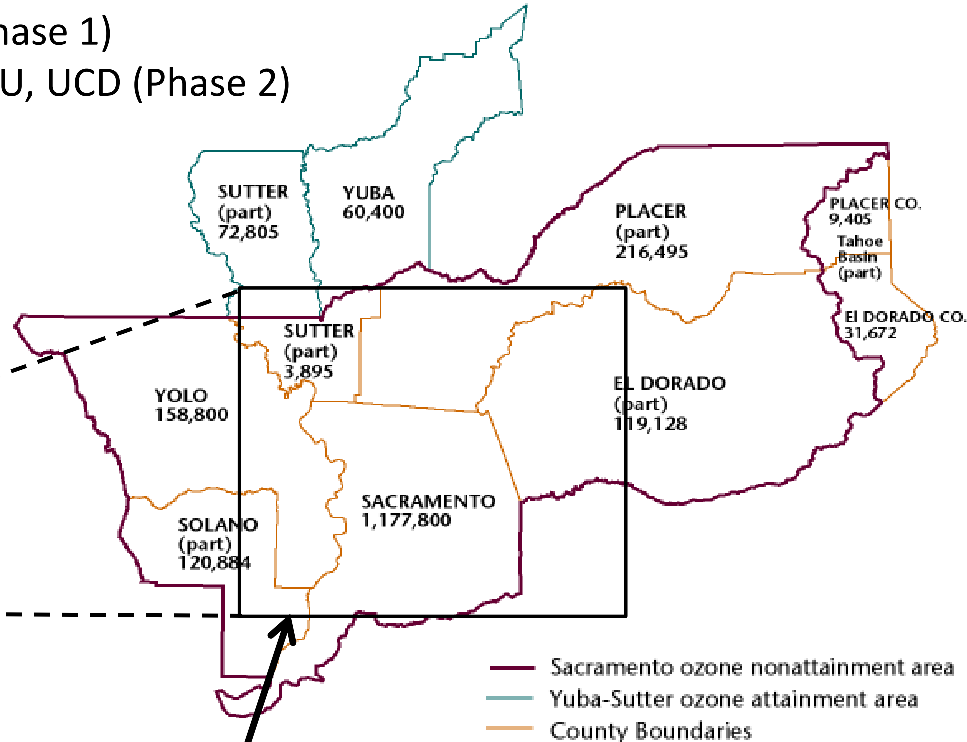
Sacramento Metropolitan AQMD UFFCA (SIP voluntary measure)

→ SMAQMD, STF, CUFR (Control Measure – Phase 1)
→ Altostratus Inc., Alpine Geophysics, LLC, SJSU, UCD (Phase 2)





1km domain
4km domain

Map background source: Feather River AQMD

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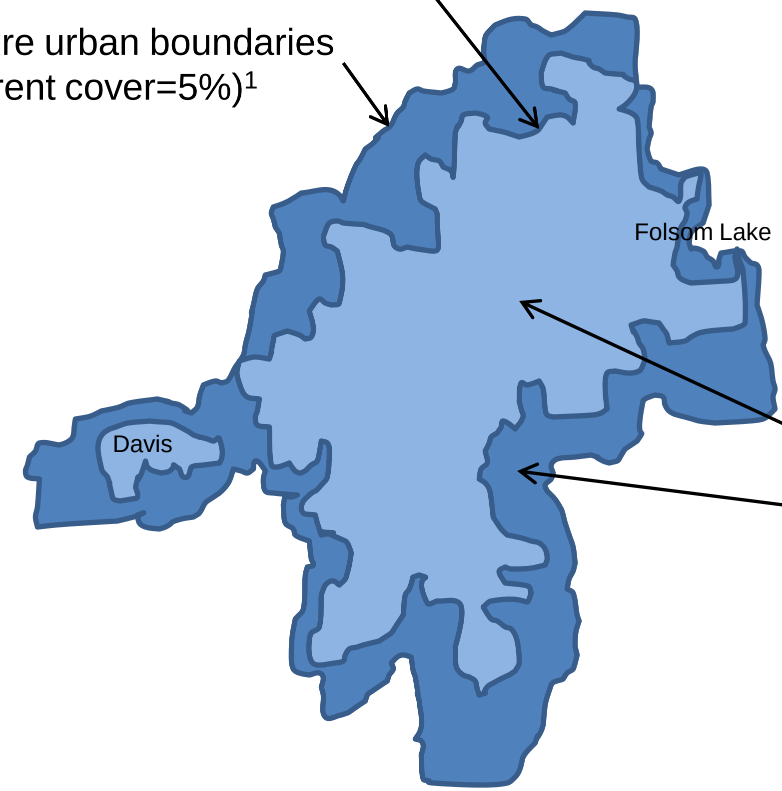
UFFCA PROJECT OVERVIEW

URBAN FOREST SCENARIOS

Current urban boundaries ~ 1470 km^2 (current cover=14%, 7M trees)[1]

Future urban boundaries (current cover=5%)[1]



Scenario / #trees	2002 (base)	2018	2023
Business as usual	×	×	×
Low-emitter mix 1M		×	×
Functional mix 1M		×	×
Low emitter mix 7.3M			×
Functional mix 7.3M			×

Strategy/ scenario	AQ impact pathway
Replacement	Δ emissions
Canopy increase	Δ meteorology + Δ emissions

[1] R. Kerth/UFORE; Simpson and McPherson (2006)

FUTURE RESEARCH NEEDS

- Identify potential PM_{10}/$PM_{2.5}$ impacts of UHI control
- Multi-episodic / seasonal / annual assessments of potential impacts
- Sub-region-specific implementation scenarios and modeling
- Develop more robust credit estimates / equivalent emission reductions
- Model improvements; resolution / dynamics / thermodynamics / soil
- Urbanization of photochemical models
- Vegetation canopy models; in-canopy vertical variations of TKE, K↓, T
- Fine-resolution data for modeling
- Development of UCP data / NUDAPT and surface characterization
- Assessment of impacts on "heat-pollution" waves; present/future

FUTURE UHI PIER PROJECT Objectives:

- Multi-episodic (over 15-20 years) modeling and analysis of potential air-quality benefits and impacts of heat island mitigation (episode selection: marginal, average, and worst-case scenarios)
- Seasonal (several summers) modeling and analysis; Annual
- Conversion of air-quality impacts into emission-reduction equivalents for credit estimates
- Modeling and analysis (scoping study) of meteorological and air-quality impacts of large-scale deployment of solar systems and provision of initial design guidelines

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*** Resulting from PIER funded UHI modeling study**