Urban microclimate and building energy: Energy and environmental aspects of urban heat islands

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28 October 2015

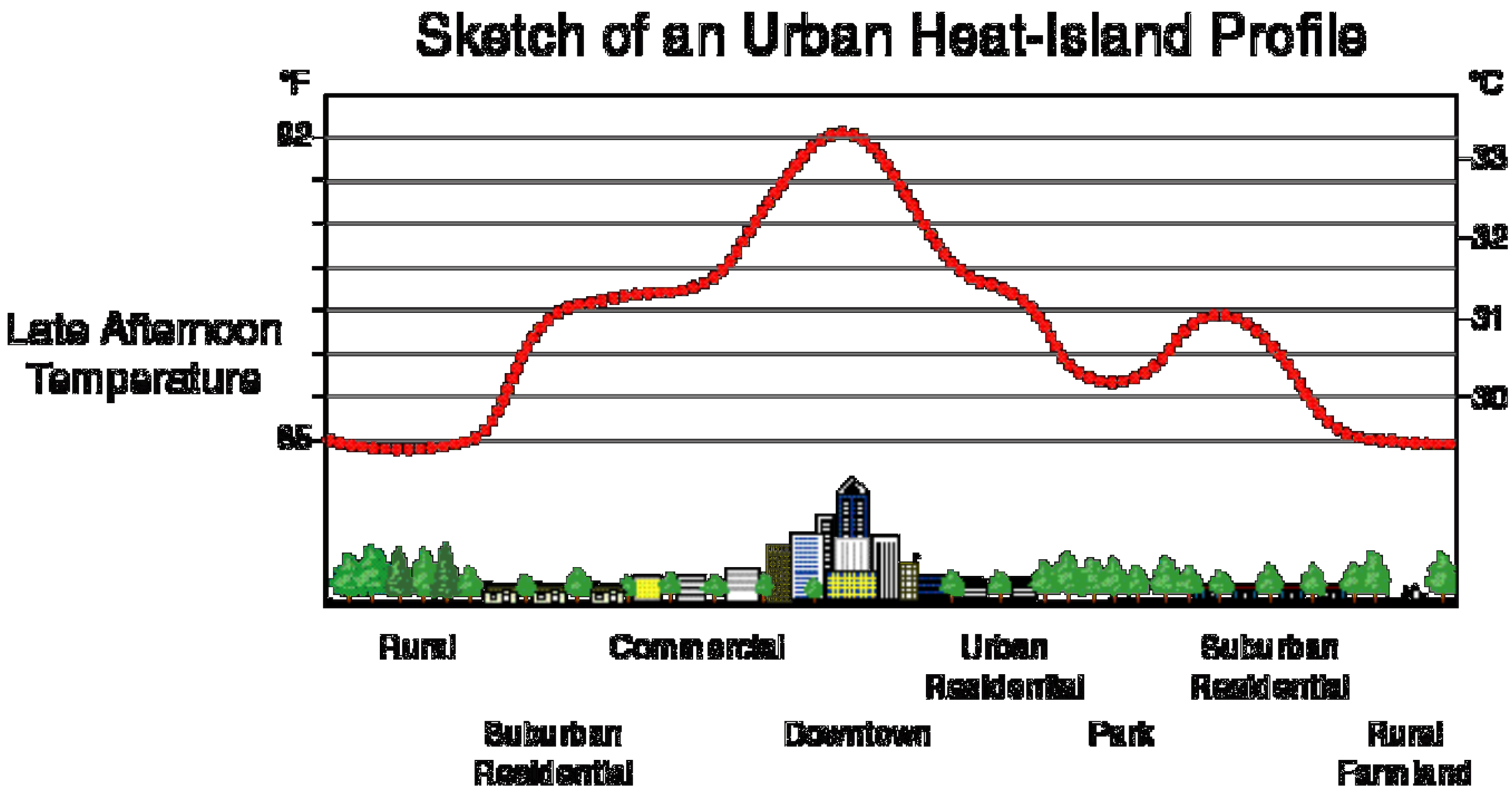
SIMUREX ÉCOLE THÉMATIQUE,

du 26 au 30 octobre 2015, Porticcio, Corse

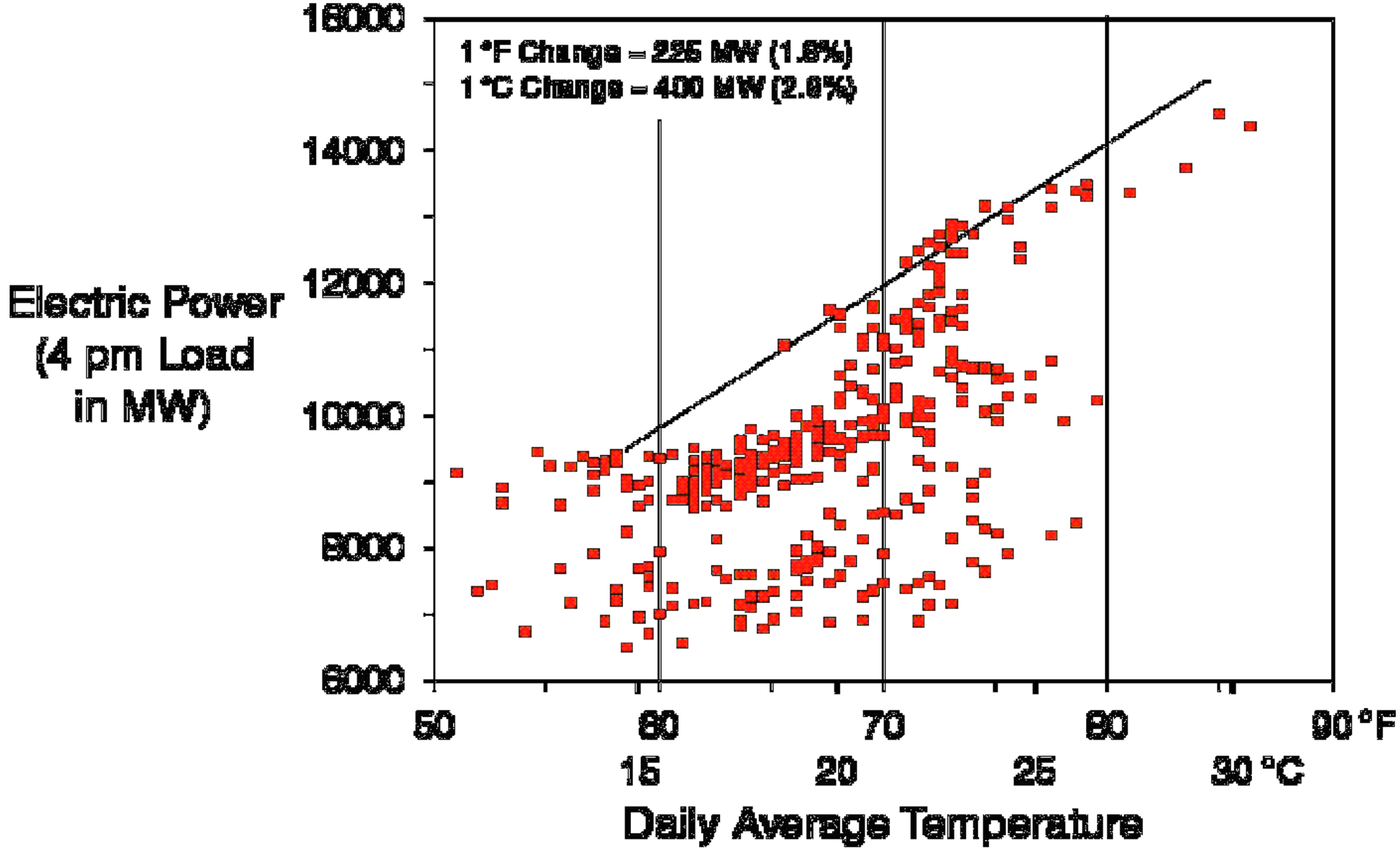
Outline

- General background
- Urban climate effects on
  - Energy
  - Meteorological
  - Air quality
  - Global cooling
  - Comfort
- France focus

What Is a Heat Island?

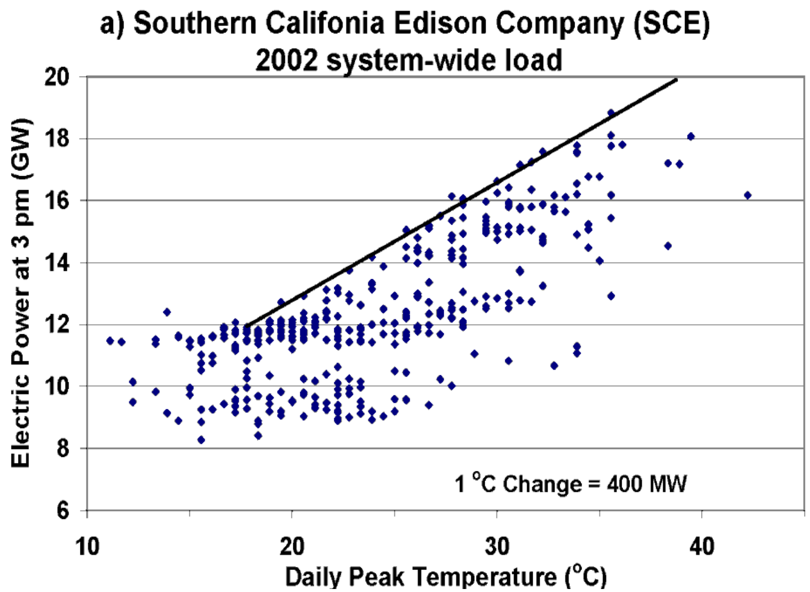


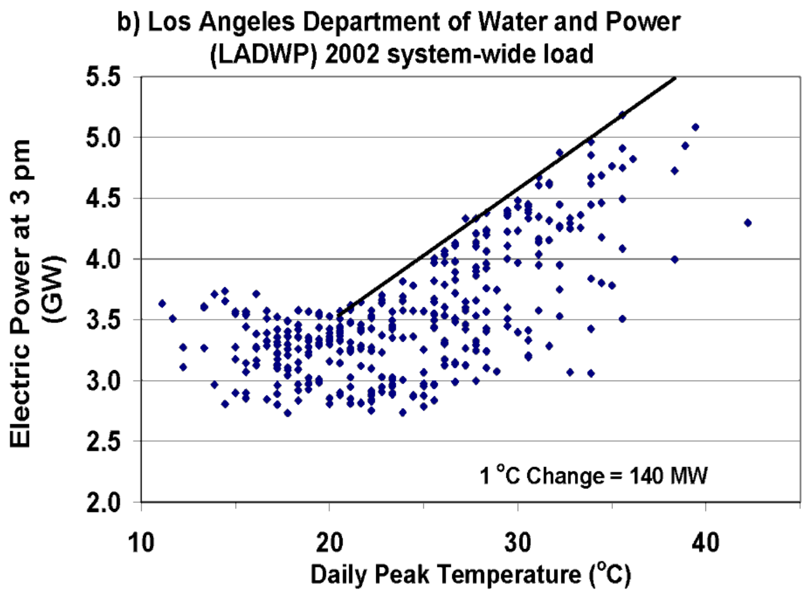
Effect of Temperature Rise on Southern California Edison Peak Load (1988)



Effect of temperature rise on utility peak load

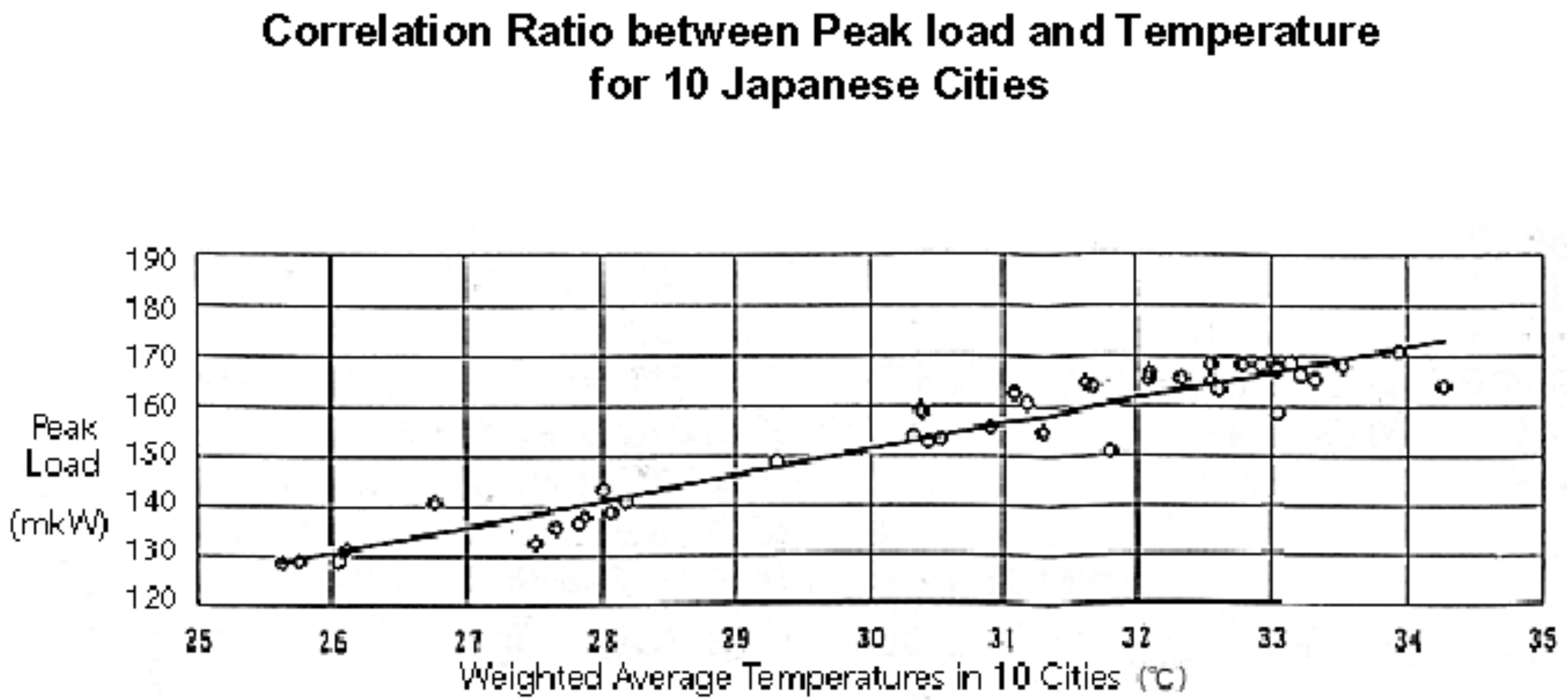
1 °C = 600 MW





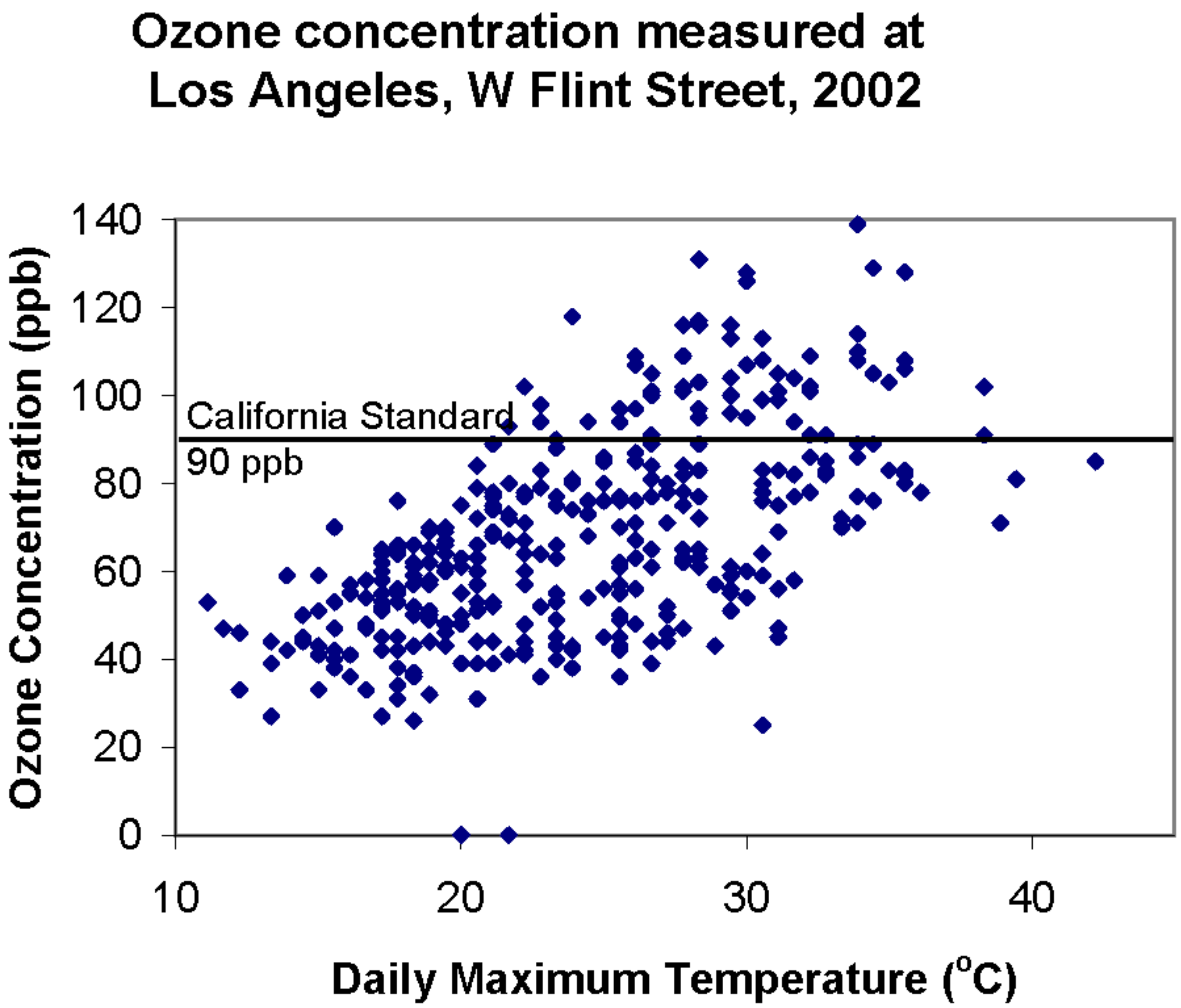
Japan: High temperatures cause peak demand

Source: Hiroji Ohta, FEPC Chairman, 10 September 1999

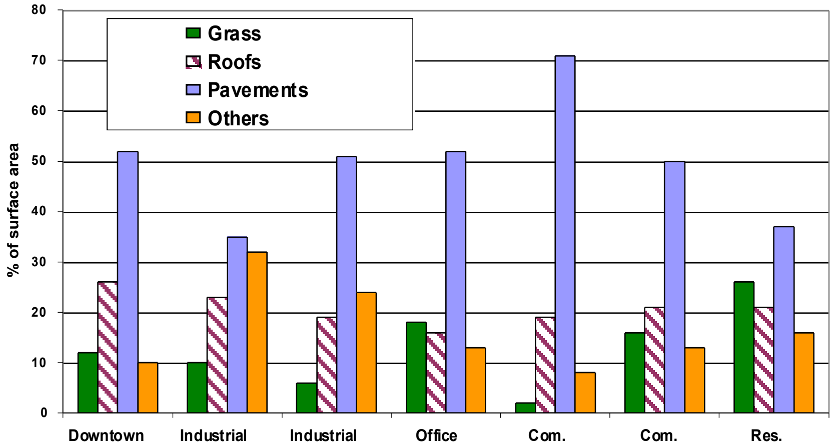


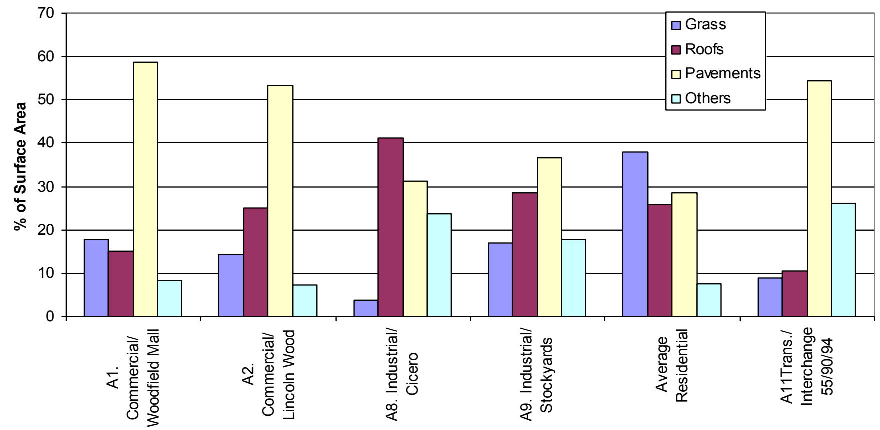
1 °C = 5 GW

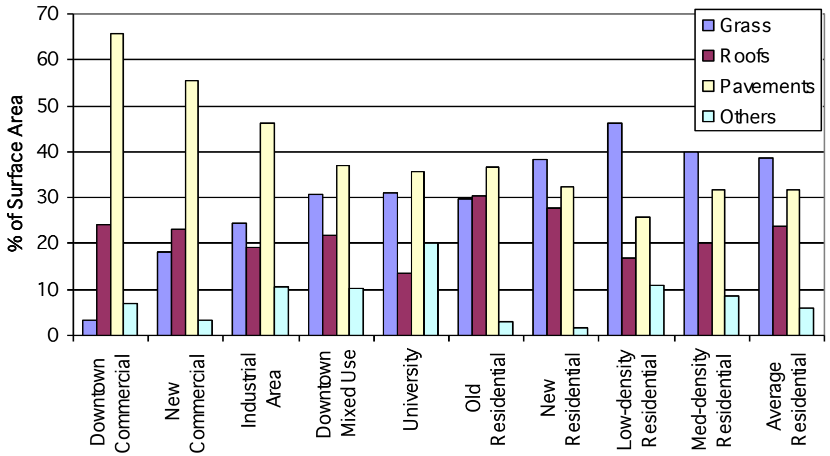
Effect of temperature rise on peak ozone concentration

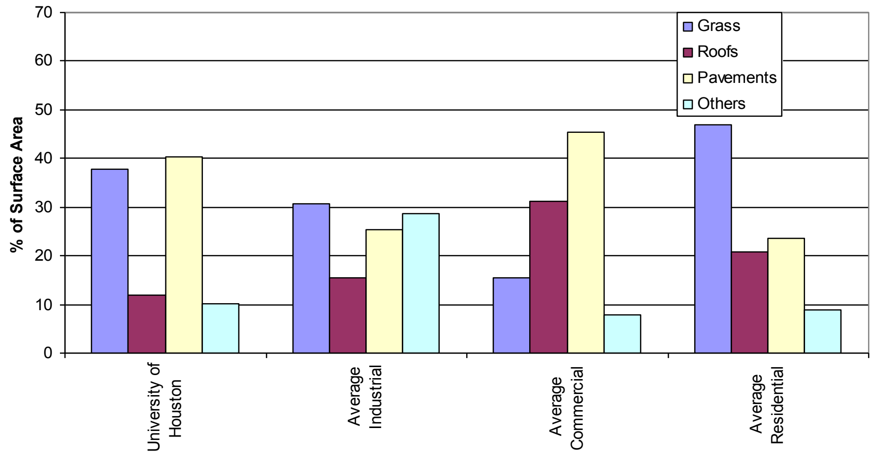


Land Cover in Sacramento CA; Chicago IL; Salt Lake City UT; Houston TX--Much Pavement

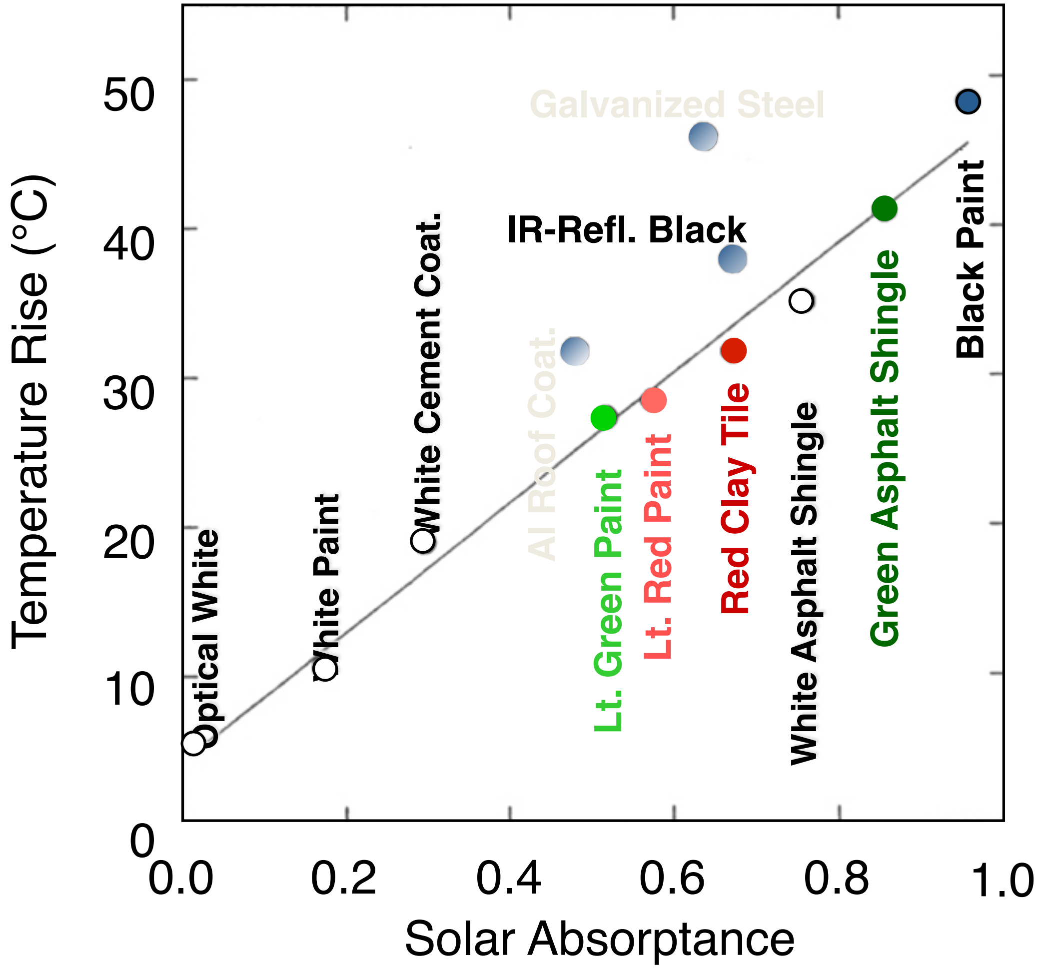




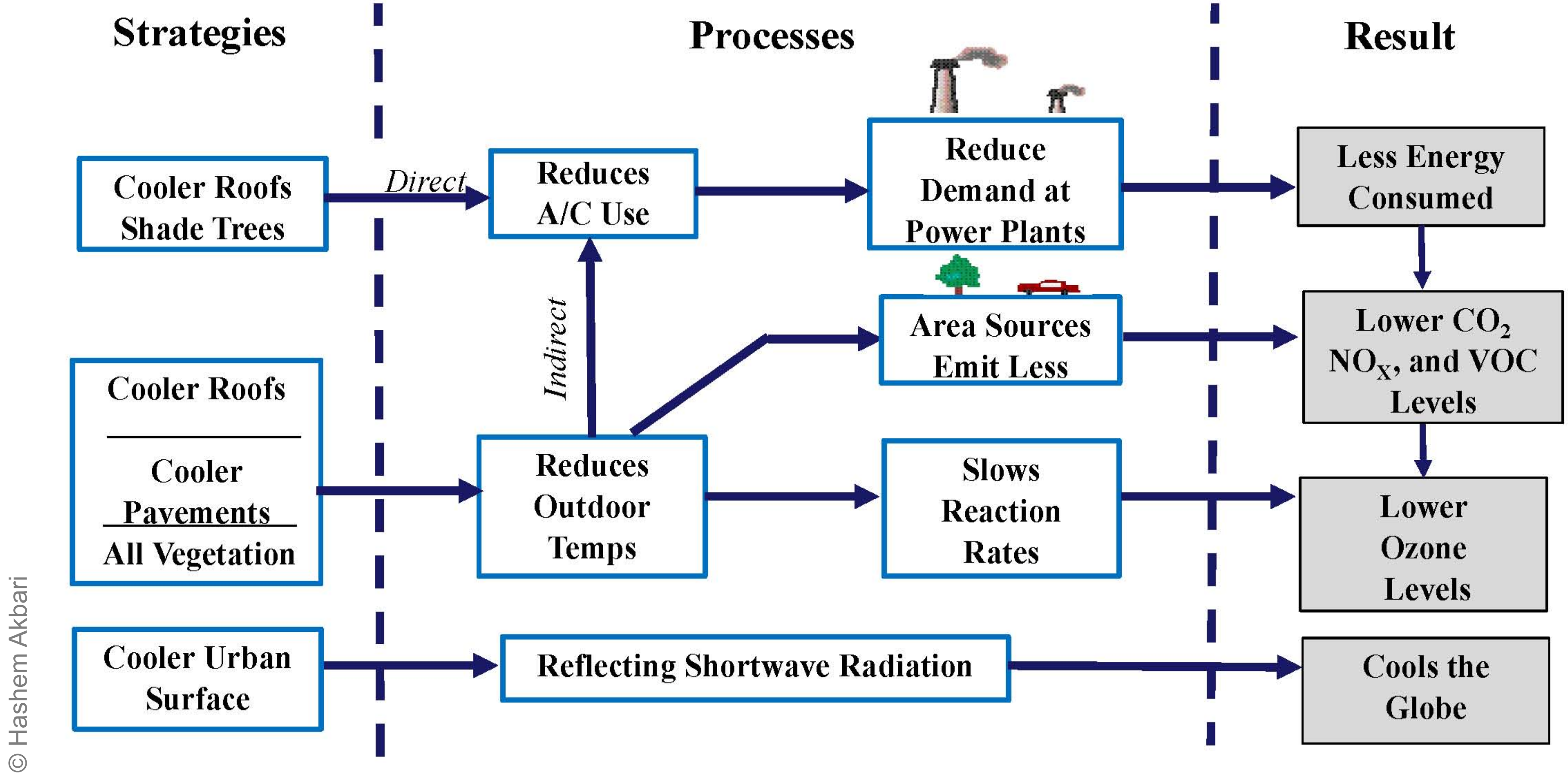




Temperature rise of various materials in sunlight



Effects of heat island countermeasures



Energy

- Buildings
  – EnergyPlus, DOE-2, TRANSYS, …
  – New algorithms
- Transportation
- Industry
- Infrastructure

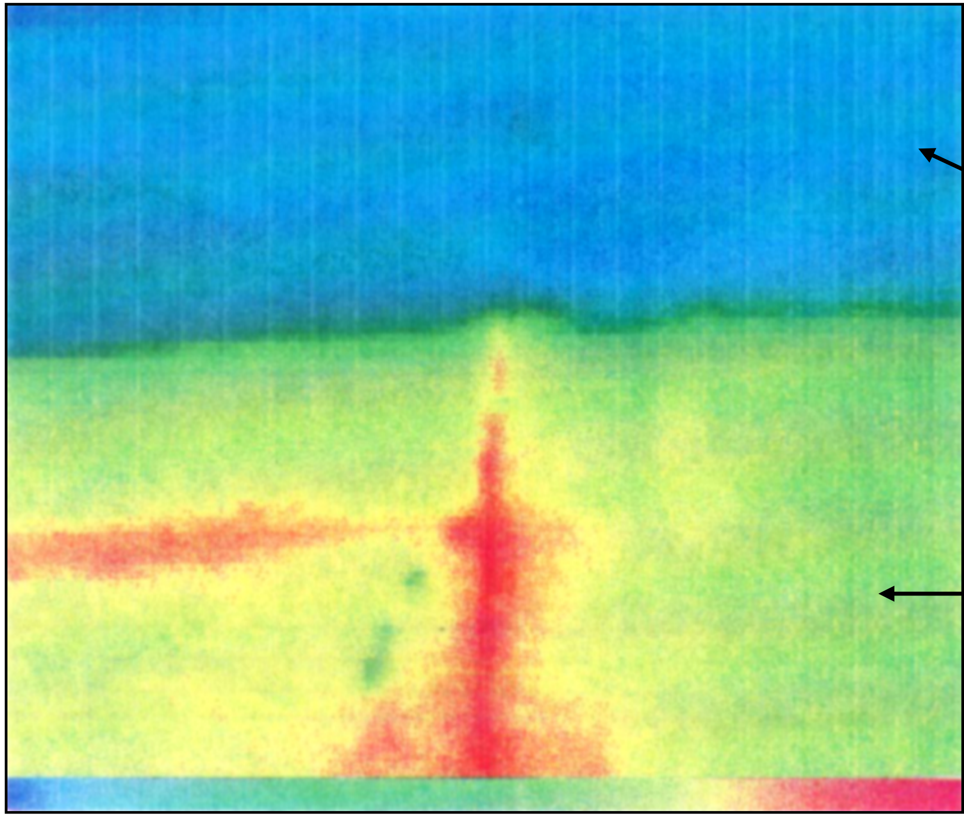
Kaiser Permanente medical office building, Davis CA

Demonstration of Cool Roofs in 3 Commercial Buildings

Kaiser Permanente rooftop

Demonstration of Cool Roofs in 3 Commercial Buildings

Roof-coating edge Infra-Red image



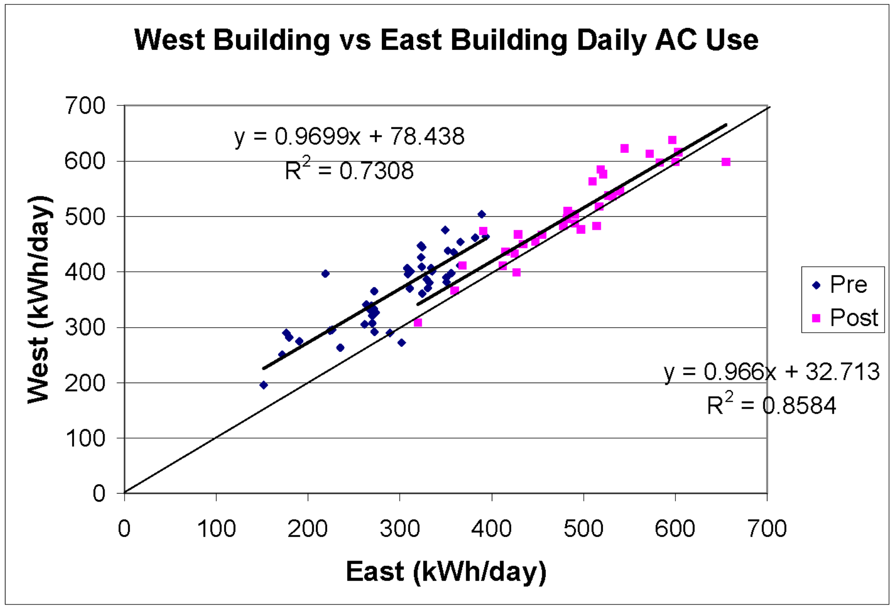
Demonstration of Cool Roofs in 3 Commercial Buildings

Air-conditioning savings

	Monitored kWh/day		Normalized post kWh/day for pre T_{out}	Estimated savings	
	pre	post		Δ kWh/day	%
Davis	1094	915	896±15	198±15	18±1
Gilroy	675	658	589±7	86±7	13±1
San Jose	713	730	700±6	13±6	2±1

Cool roof saves 10%-20% air-conditioning for area under the roof

- U.S.
- Japan
- Europe
- Asia
- Middle East
- China
- India (Hyderabad demos; see graph at right)



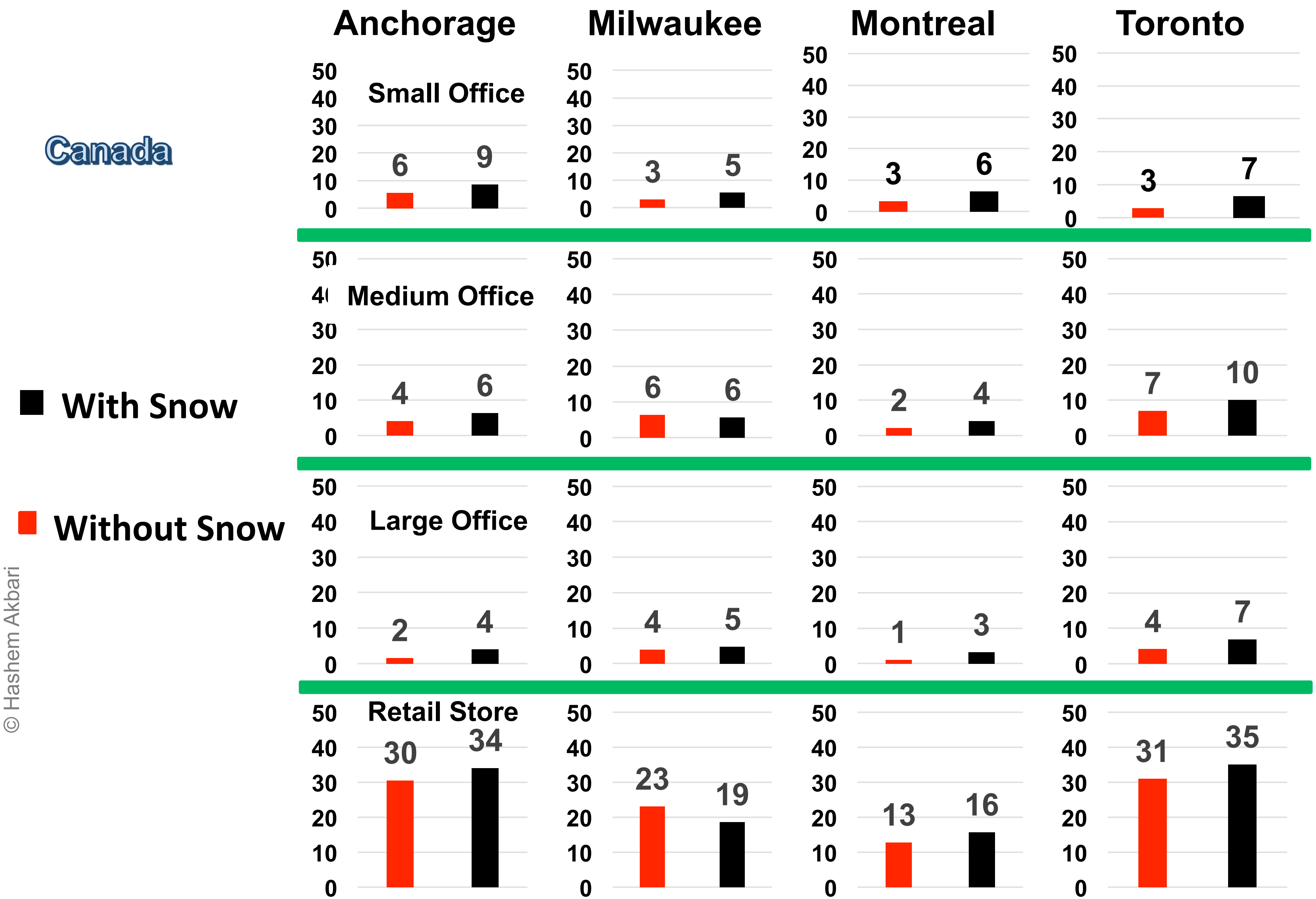
Cooling vs. heating: Rule of thumb

- Anywhere in the world, if you need cooling in summer
  - A cool roof saves you money
  - The heating penalty is less than 30% of cooling energy saving
- If you do not have cooling and summer comfort is not an issue, cool roofs will not save you money
- If you are considering buying AC, first consider a cool roof
- A cool roof may result in a down-size in air-handling units and actually save you electricity in heating season
- Cool roofs also cool the globe

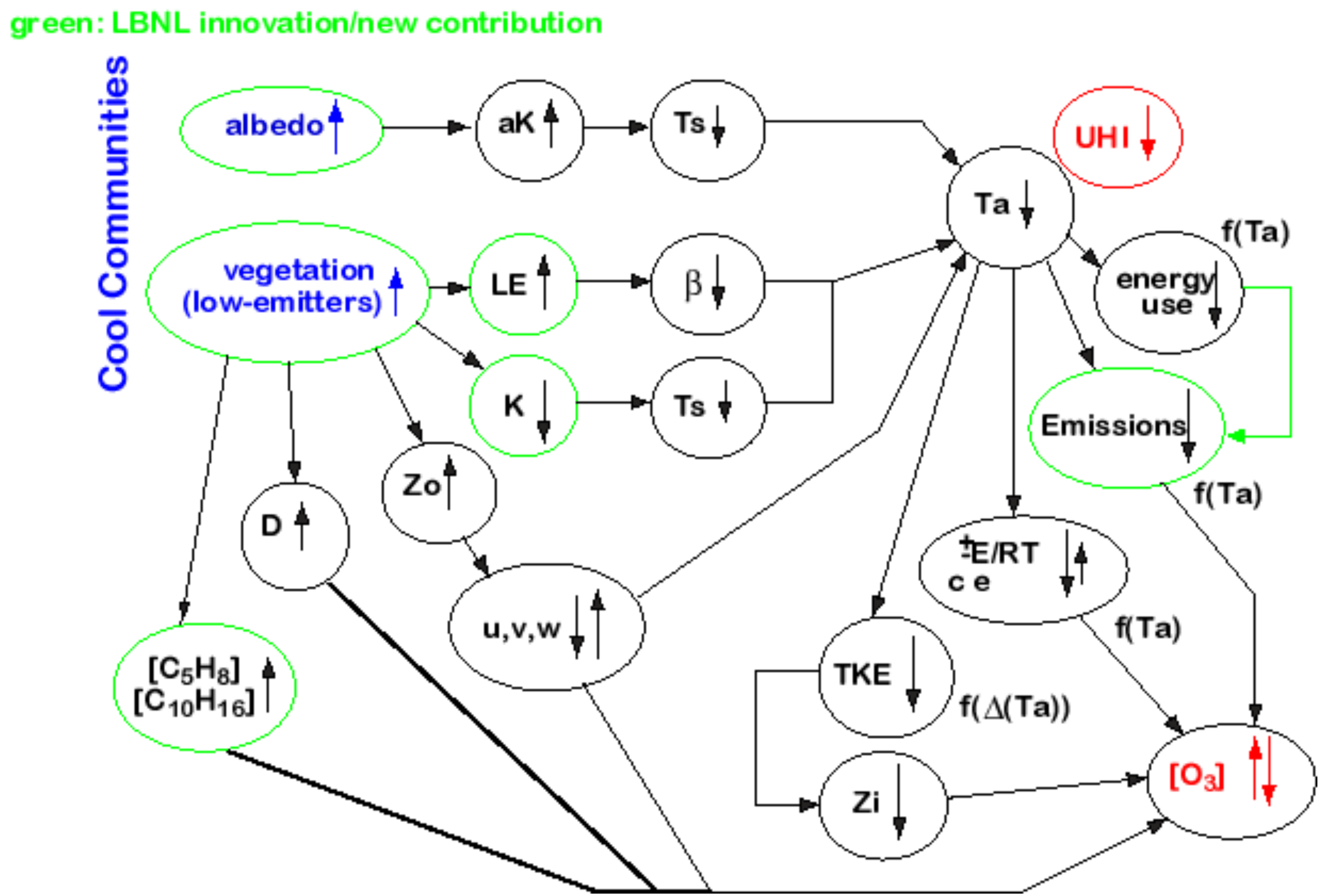
Why winter heating penalties are low?

- Days are shorter
- Sun angle on a roof is lower
- Sky is cloudier
- Most heating happens in the early morning or evening hours, when there is no Sun
- Roofs are covered by snow

Cool roofs in cold climates: Annual cool roof savings ($/100$m^2$roof) for new buildings with gas-heating systems



Meteorology and O_3 air quality: Basics



Modeling tools

- Meteorological
  - Colorado State University Mesoscale Model (CSUMM/SAIMM)
  - PSU/NCAR MM5 modeling system
  - WRF
  - San Jose State University URBMET–TVM
  - Other models, e.g. canopy-layer models
- Photochemical
  - Urban Airshed Model (UAM)
  - WRF-Chem
  - MAQSIP/EDSS modeling system
  - CIT (Caltech) airshed model
  - Others, e.g. Elfin, emissions pre-processors, EMFAC, DTIM

Meteorological models

Conservation relations

$$\frac{\partial \rho}{\partial t} = -(\nabla \cdot \rho \vec{V}) \qquad (mass)$$

$$\frac{\partial \theta}{\partial t} = -\vec{V} \cdot \nabla \theta + S_\theta \qquad (potential\ temperature)$$

$$\frac{\partial V}{\partial t} = -\vec{V} \cdot \nabla \vec{V} - \frac{1}{\rho} \nabla p - g\vec{k} - 2\vec{\Omega} \times \vec{V} \qquad (momentum)$$

$$\frac{\partial q}{\partial t} = -\vec{V} \cdot \nabla q + S_q \qquad (water\ vapor)$$

Surface energy balance

$$(1-a)K \downarrow + L^* = \rho C_p \overline{w'\theta'} + \rho L_V \overline{w'q'} + G$$

Photochemical models

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (\vec{u} c_i) = \nabla \cdot (\vec{K} \nabla c_i) + R_i + S_i + D_i$$

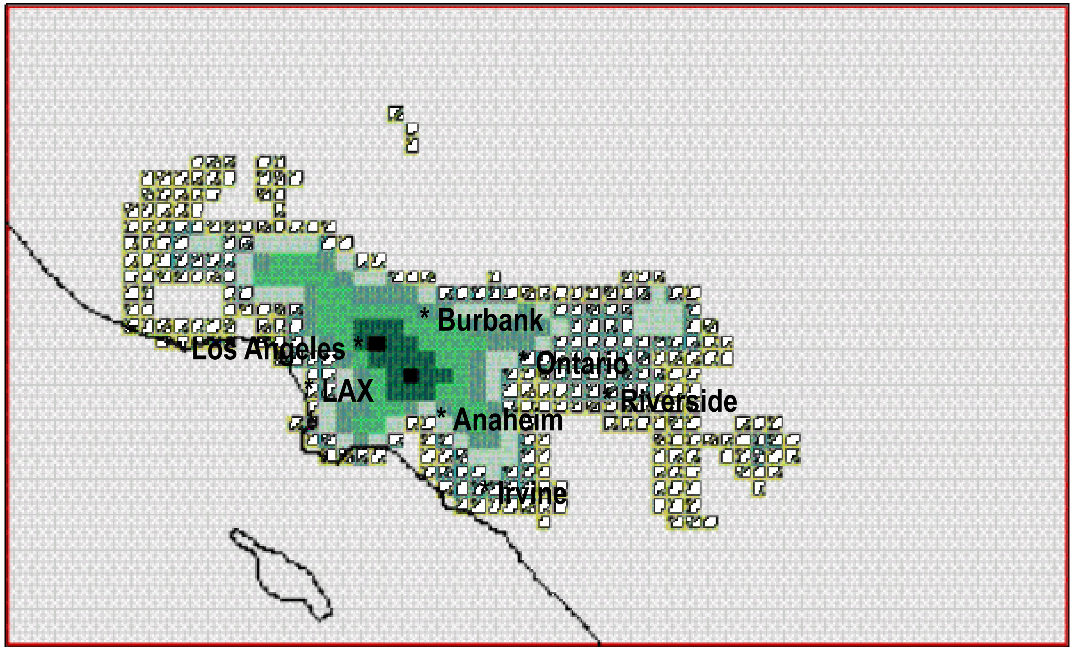
$$S_i = E_f \times A \qquad (source\ term)$$

$$D_i = c_i \times V_d \qquad (deposition\ term)$$

$$R_i = \ \sim 200 \rightarrow \ \sim 80\ reactions\ (CB\text{-}4) \qquad (transformation\ term)$$

Simulated air temperature difference: Adding 11 M trees

Los Angeles, 3 p.m., August 28



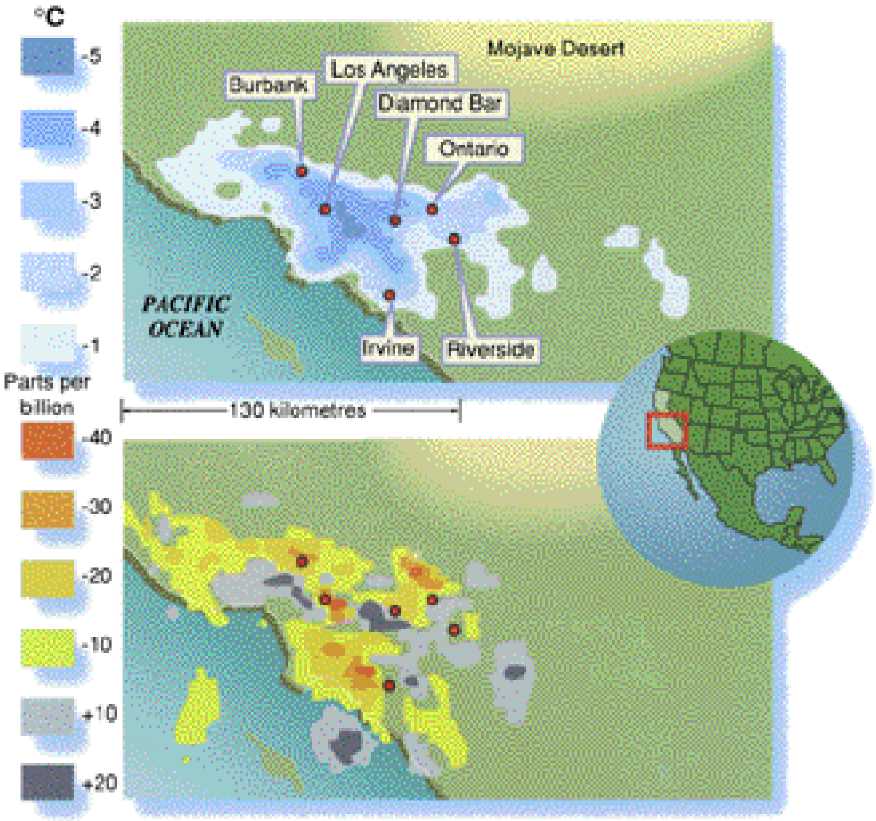
Temperature difference (°C)

-3.5 -3.0 -2.5 -2.0
-1.5 -1.0 -0.5

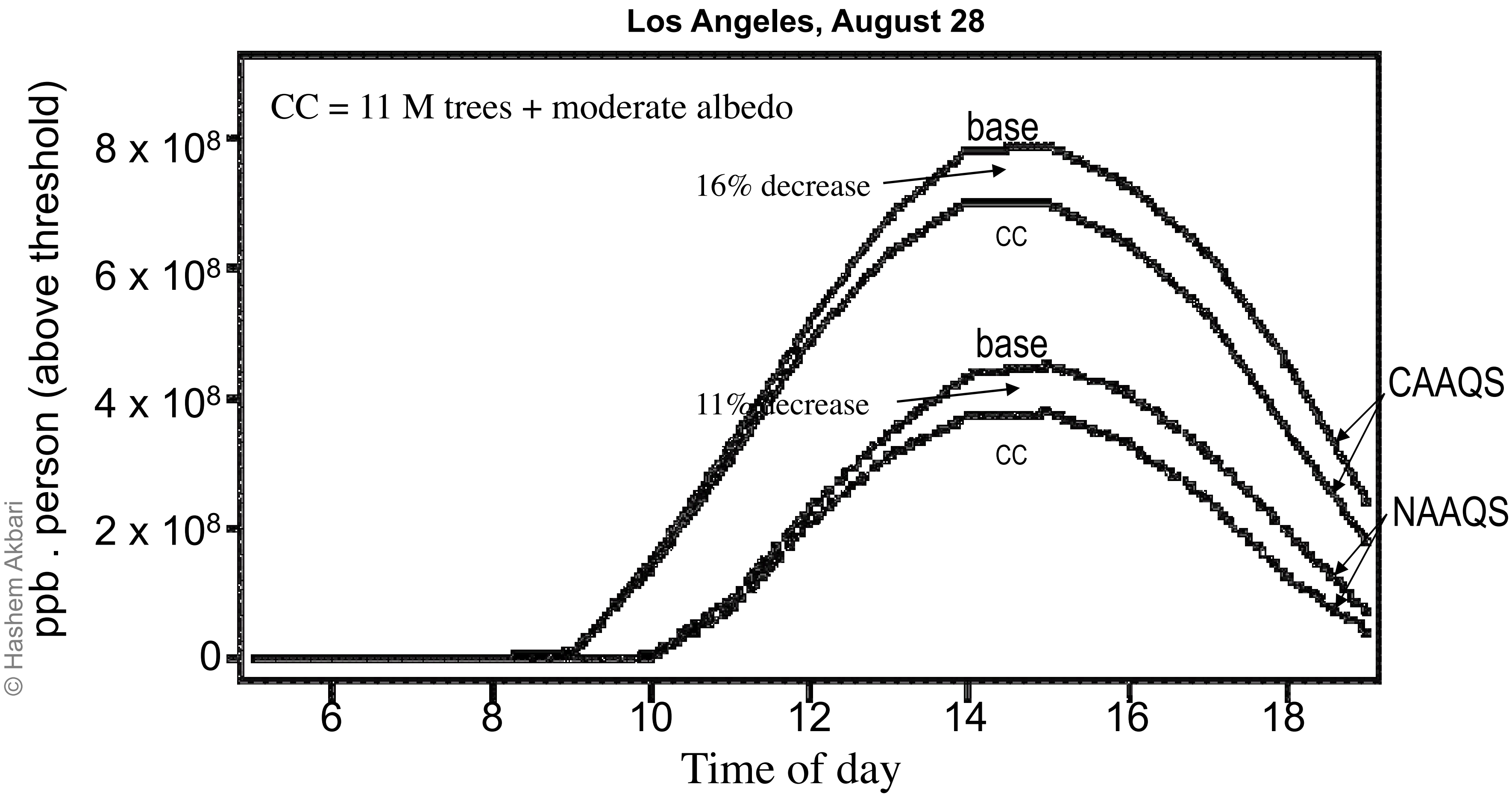
Simulated meteorology and air-quality impacts in LA

Temperature Change

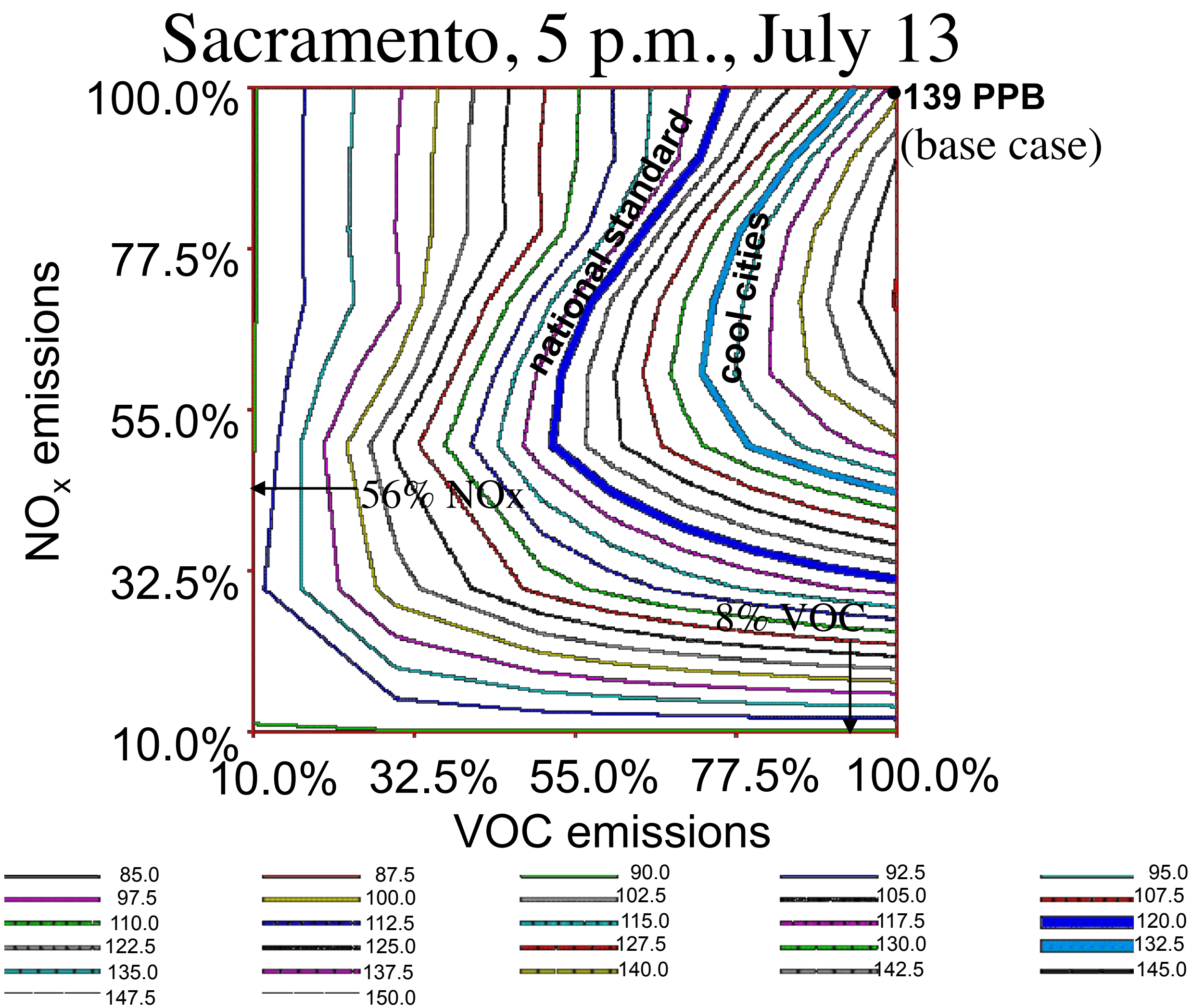
Ozone Concentration Change



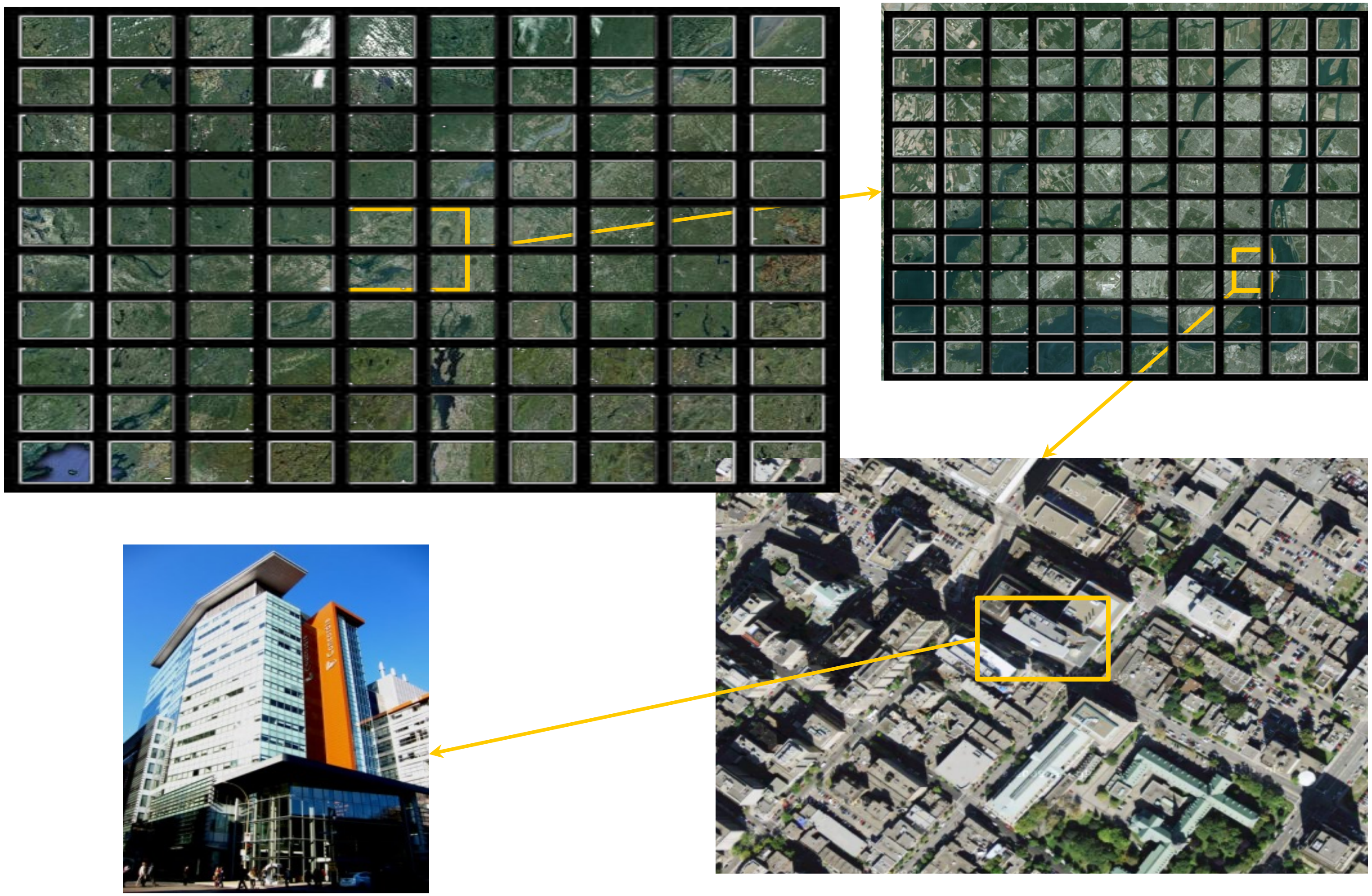
Simulated population-weighted exceedence exposure to Ozone



UAM-generated [O_3] peak isopleths (for 1–2°C decrease)

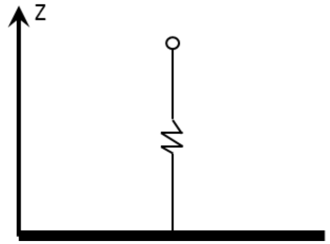


Urban climate

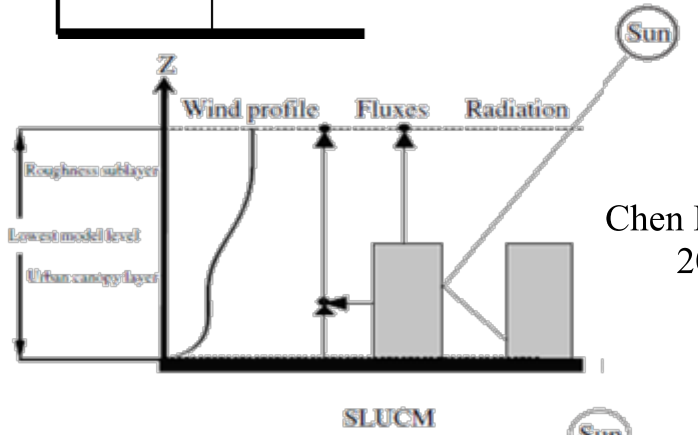


The role of urban canopy models

- Slab model
  - ✓ Chen and Dudhia (2001)

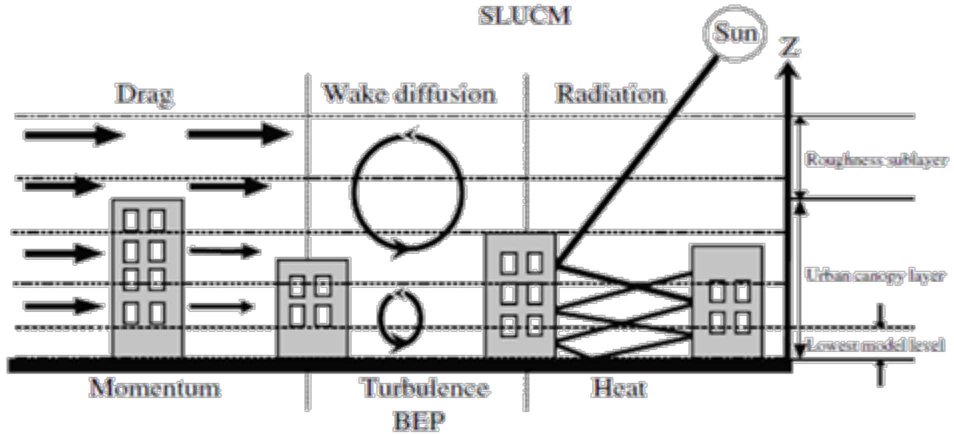


- Single-layer
  - ✓ Kusaka et al. (2001, 2004)

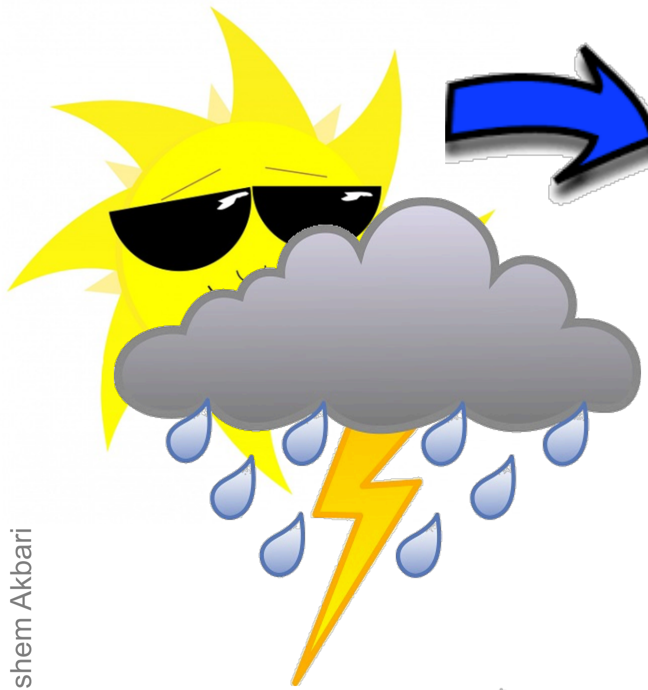


Chen F., et al., 2011.

- Multi-Layer
  - ✓ Martilli et al. (2002)



The role of building energy models



Offline

Taha et al. (1988)
Taha (1997)
Akbari et al. (2001)

Salamanca (2010)

Online

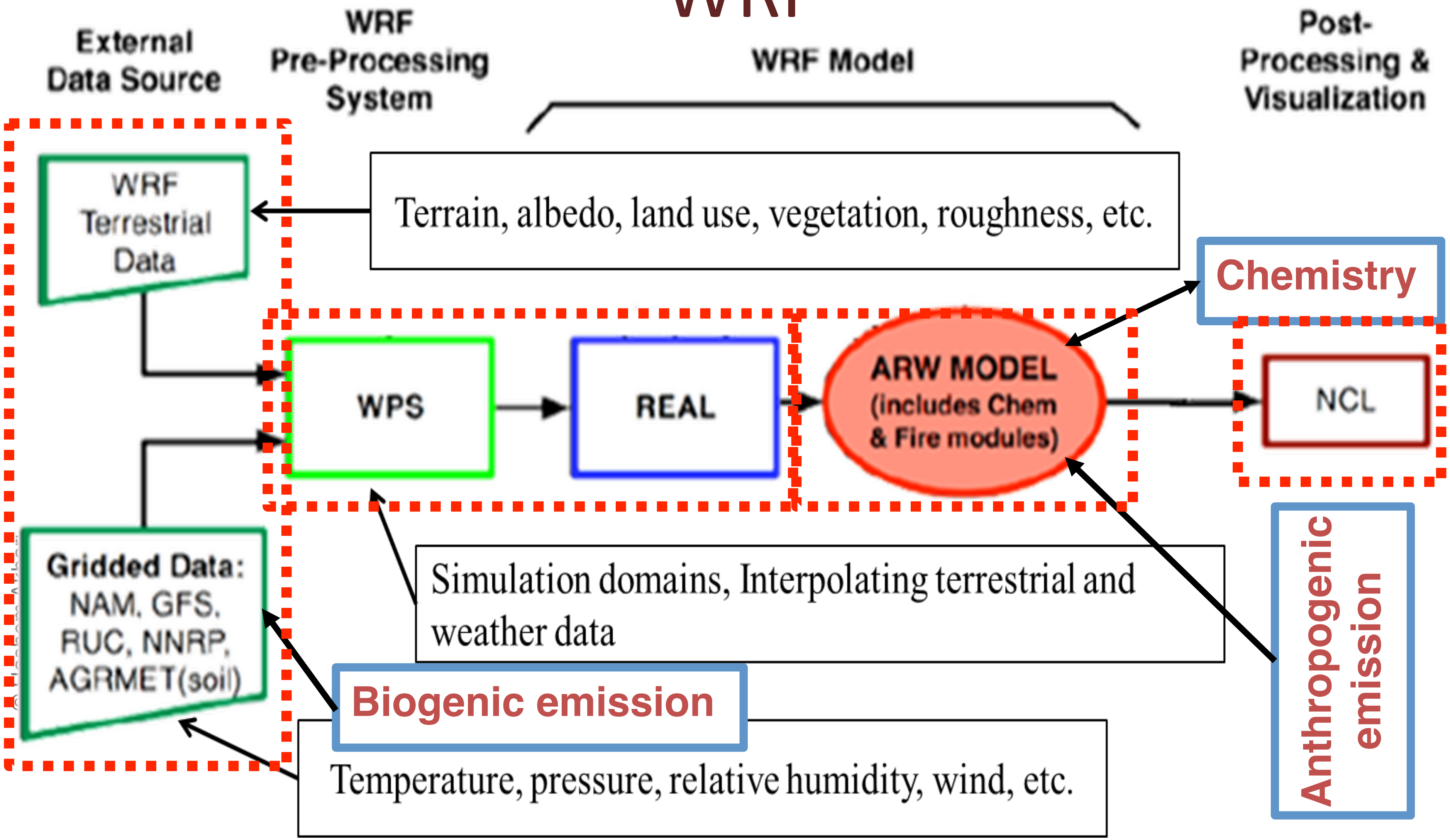
Questions to answer

- How to execute urban climate simulations using fine-resolution grids?
- What are the morphological parameters?
- How increasing the albedo and vegetation works?
- How much energy is saved in buildings?
- What is the effect on air quality by considering the heat emission from buildings?
- What is the effect on comfort?

Simulation tool

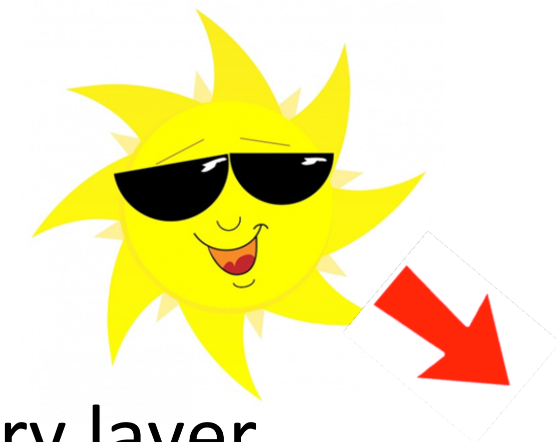
- Weather Research and Forecasting (WRF)
  - Grid size from meters to thousands of kilometers
  - Nesting
  - Urban parameterization
  - Building energy model
  - Online coupling with chemistry

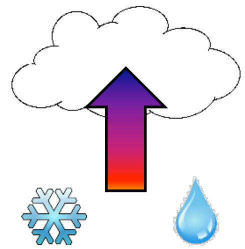
Weather Research and Forecasting model: WRF

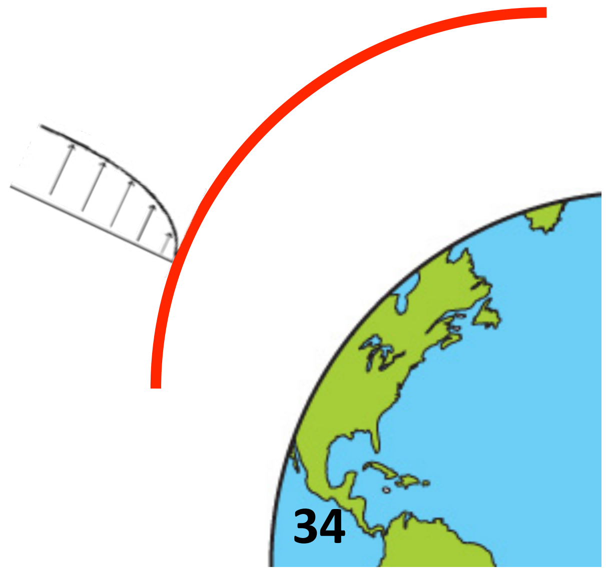


Physical models in WRF

- Microphysics
- Cumulus
- Land-surface
- Planetary boundary layer
- Atmospheric radiation







Modifications to heat flux

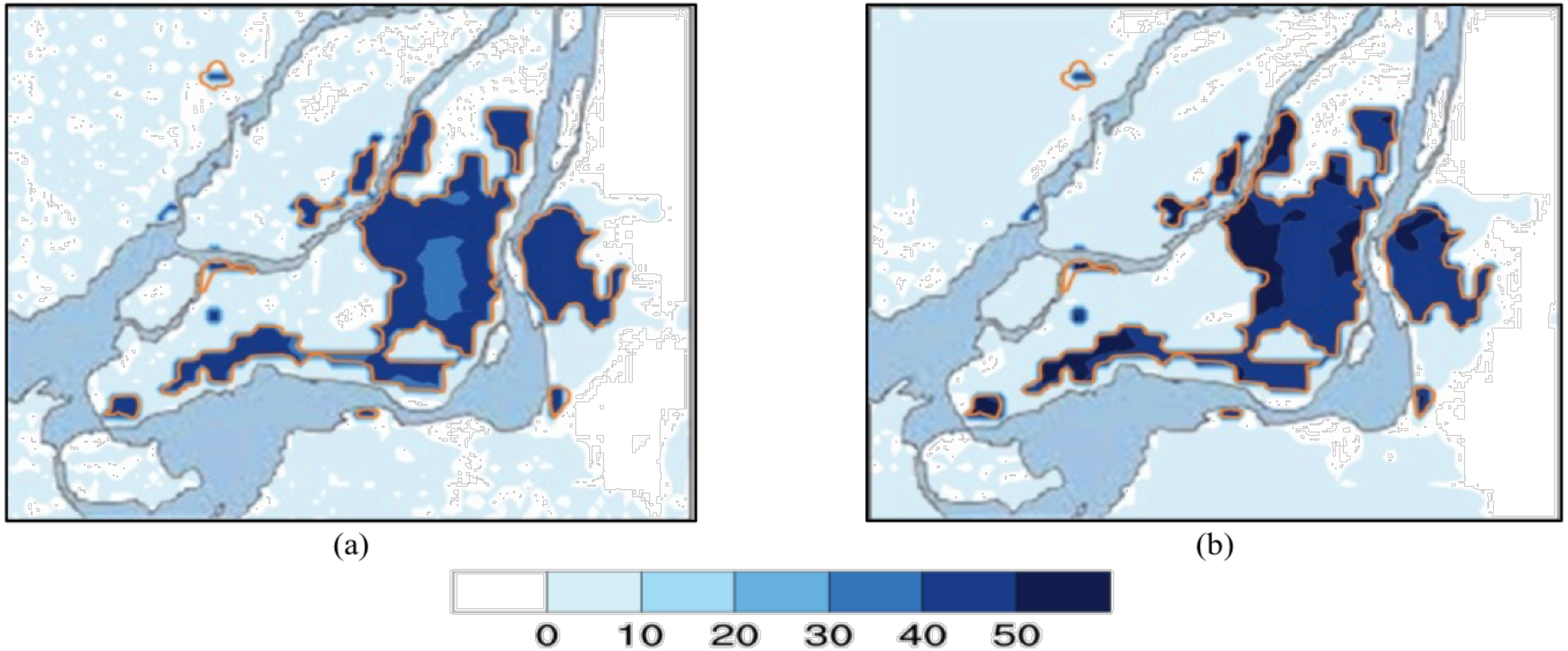
- Modifying the view factor and multi-reflection in urban canopy model
- Modifying the heat emission from buildings

$$\begin{cases} E_C = \dfrac{H_{out} + E_{out}}{COP} & \text{for cooling} \\ E_C = \dfrac{H_{out} + E_{out}}{\eta} & \text{for heating} \end{cases}$$

$$\begin{cases} Q_C = E_C(COP_{cooling} + 1) & \text{for cooling} \\ Q_C = \eta.E_C & \text{for heating} \end{cases}$$

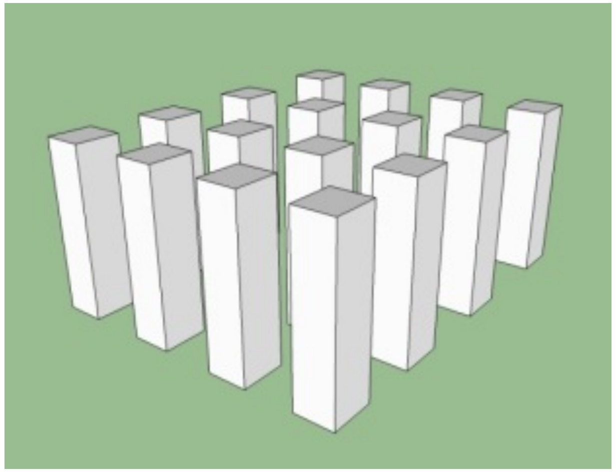
Choice of urban canopy model:
Effect of turbulence on heat flux

(a) ML-UCM and slab model (ML-slab), (b) ML-UCM and SL-UCM (ML-SL)

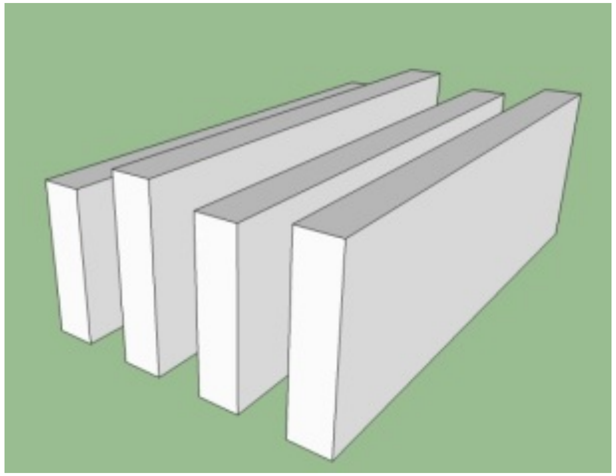


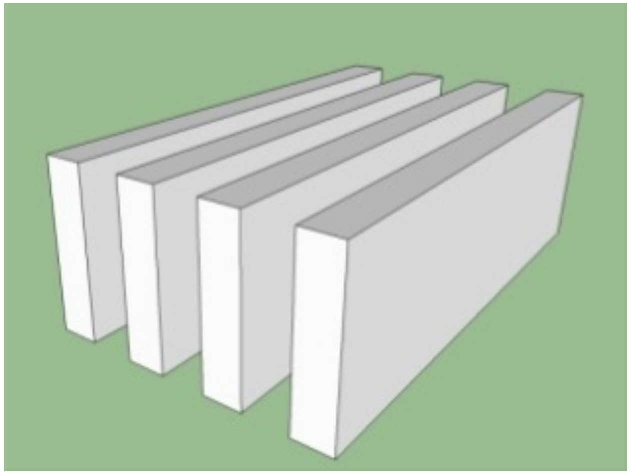
Urban morphology

- 3D urban



- 2D urban

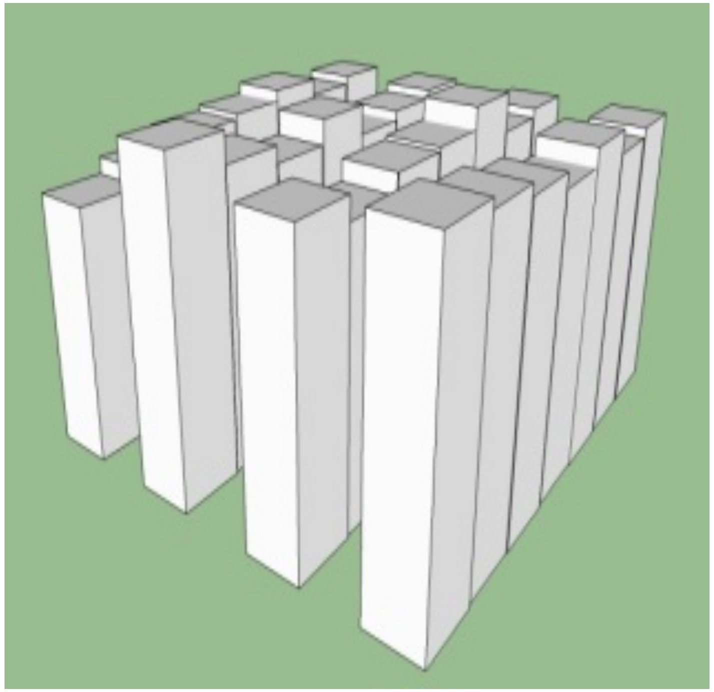




A new parameterization for SVF

- 2D canopy with variable height of buildings

SVF'=SVF+$2\lambda_f - \lambda_p$



SVF: sky view factor of 2D urban canopy

λ_f: frontal area density

λ_p: plan area density

Monthly Typical Meteorological Day (MTMD)

- Meteorological parameters

$$\delta_{i,j} = |x_i - \overline{x_m}|_j$$

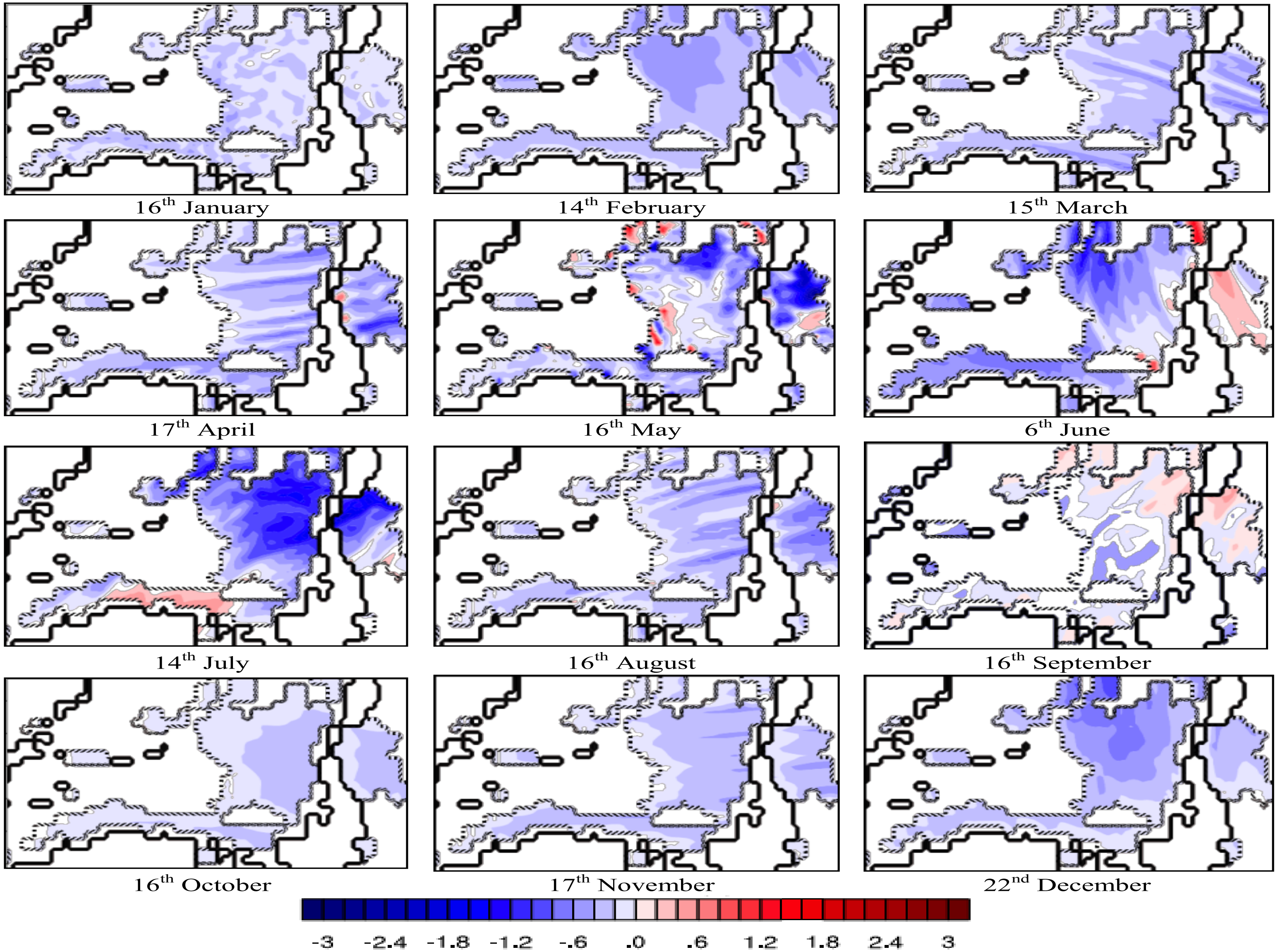
$$\sigma_j = \sum_i w_i \delta_{i,j}$$

$$MTMD_k = \min\{\sigma_j\}$$

Montreal example: Scenarios

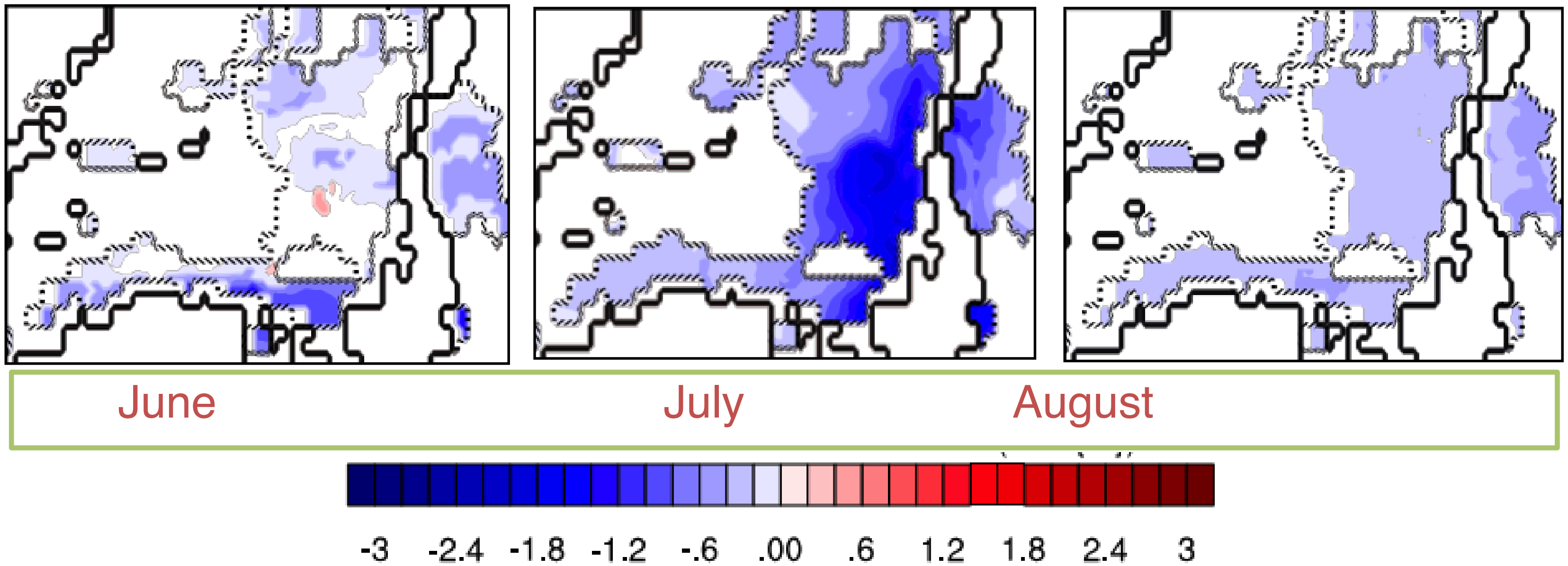
- CTRL
  - All surfaces have the albedo of 0.2
- ALBEDO
  - Roof → 0.65
  - Walls → 0.60
  - Street → 0.45

Temperature (ALBEDO-CTRL) @ 3pm



Difference in total energy of HVAC systems (ALBEDO-CTRL) [W/m^2]

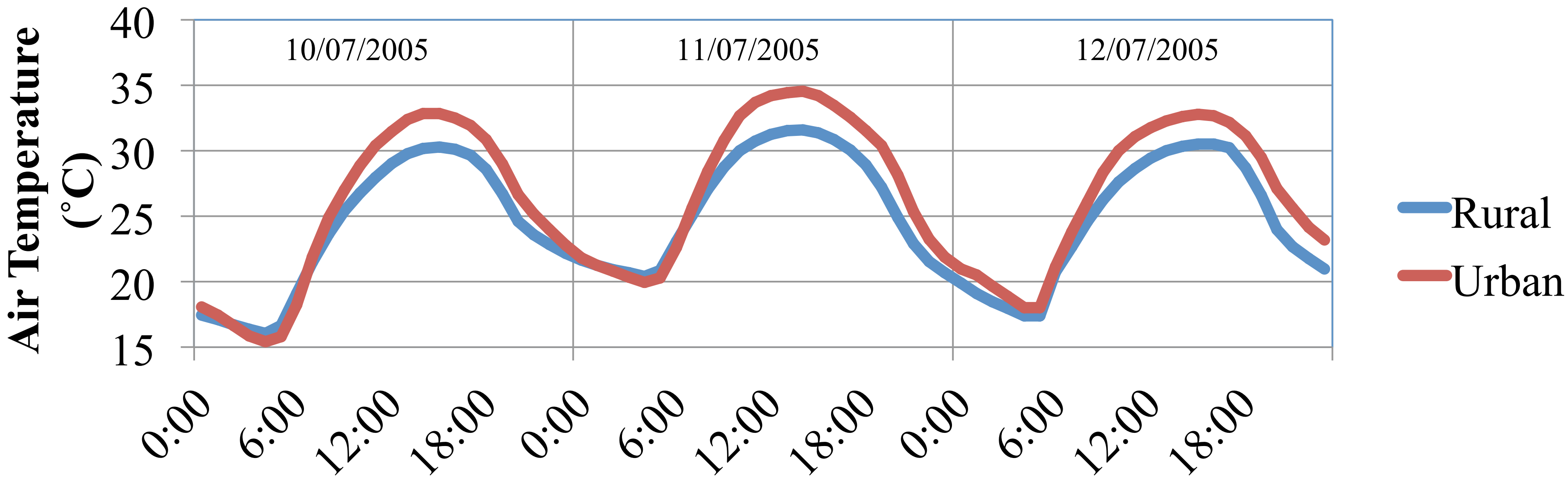
- The difference in energy consumption of HVAC systems is only noticeable in summer

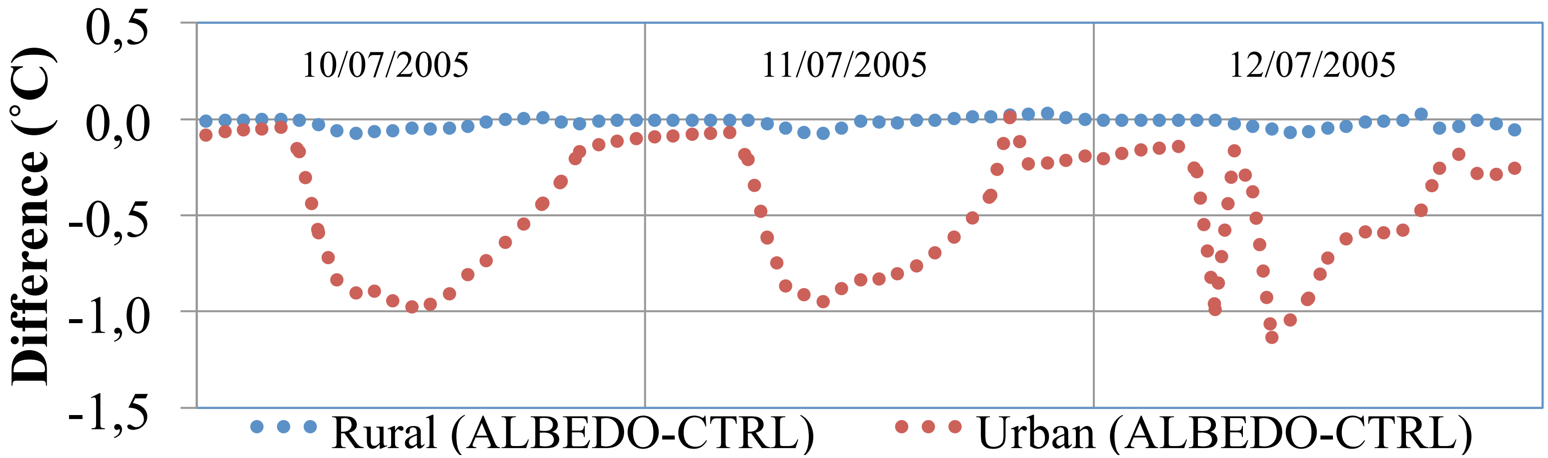


Air quality: Simulation domain and episode

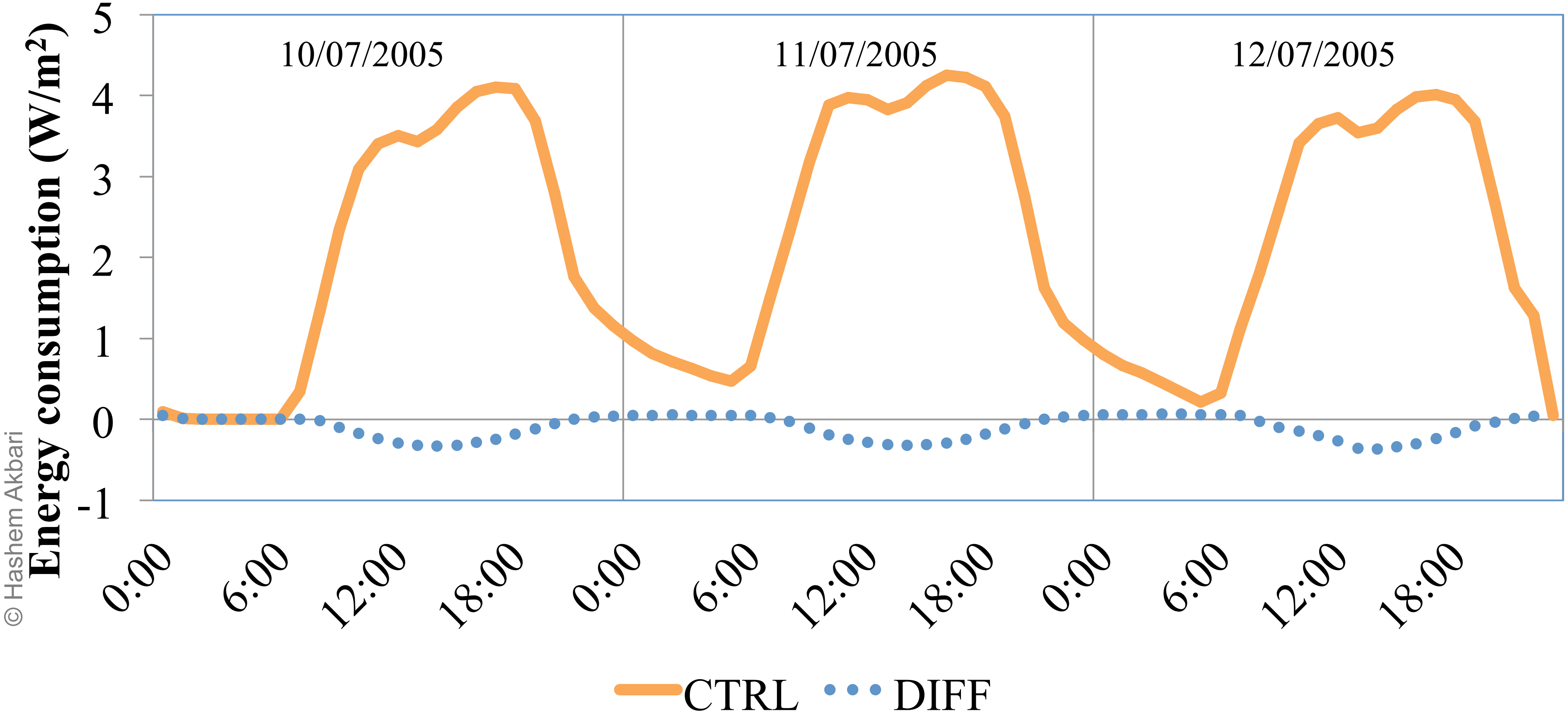
- WRF-CHEM coupled to ML-UCM and BEM
- Three consecutive days in July- 2005 (10^{th} to 12^{th} LST) with highest hourly maximum temperature
- Domain 1: 51×51 grids, grid sizes of 9 × 9 km
- Domain 2: 52×52 grids, grid sizes of 3 × 3 km
- Domain 3: 91×67 grids, grid sizes of 1 × 1 km
- The National Emission Inventory of 2005 (NEI-05) of the US-EPA

Air temperature (˚C)

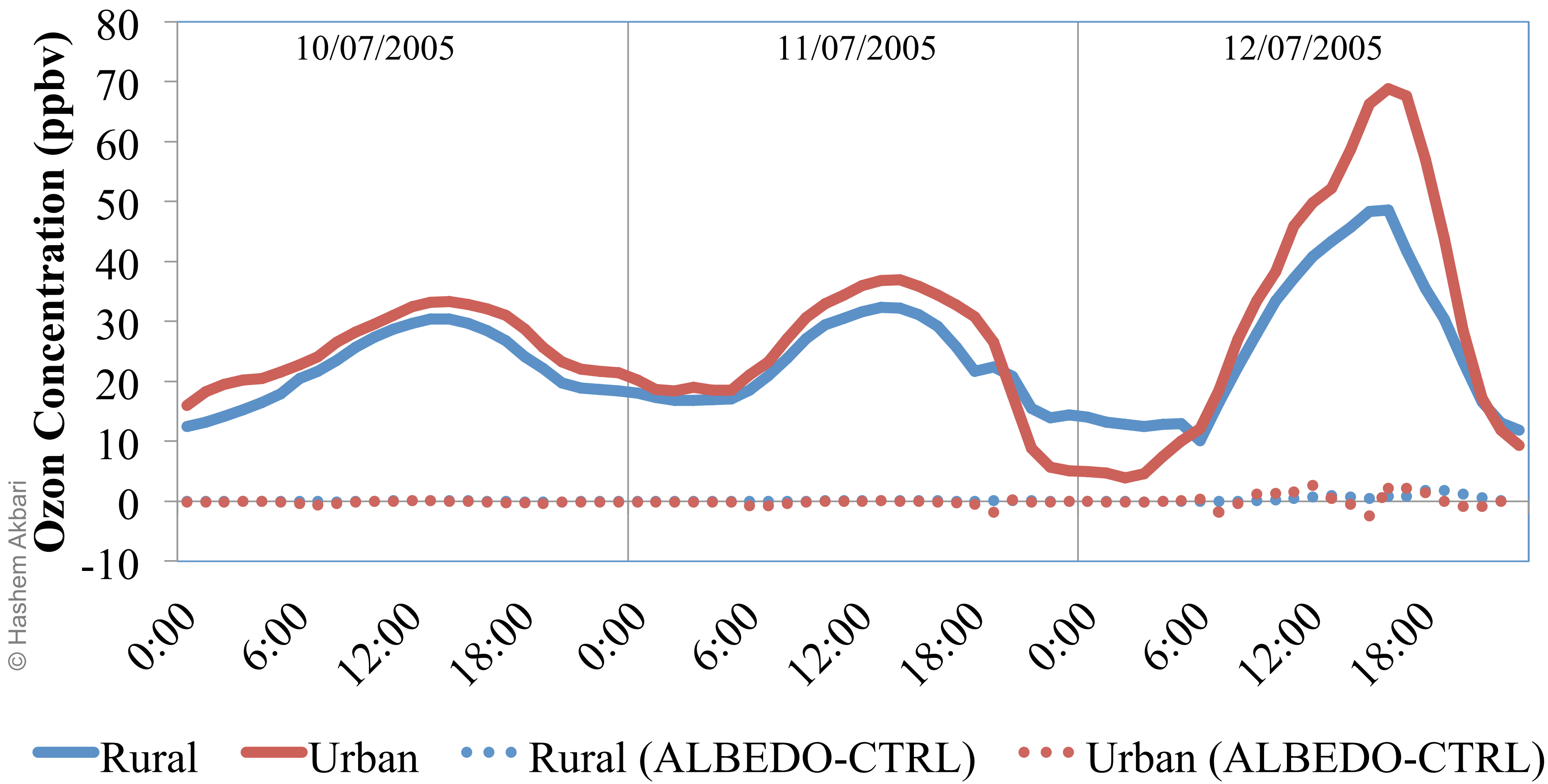




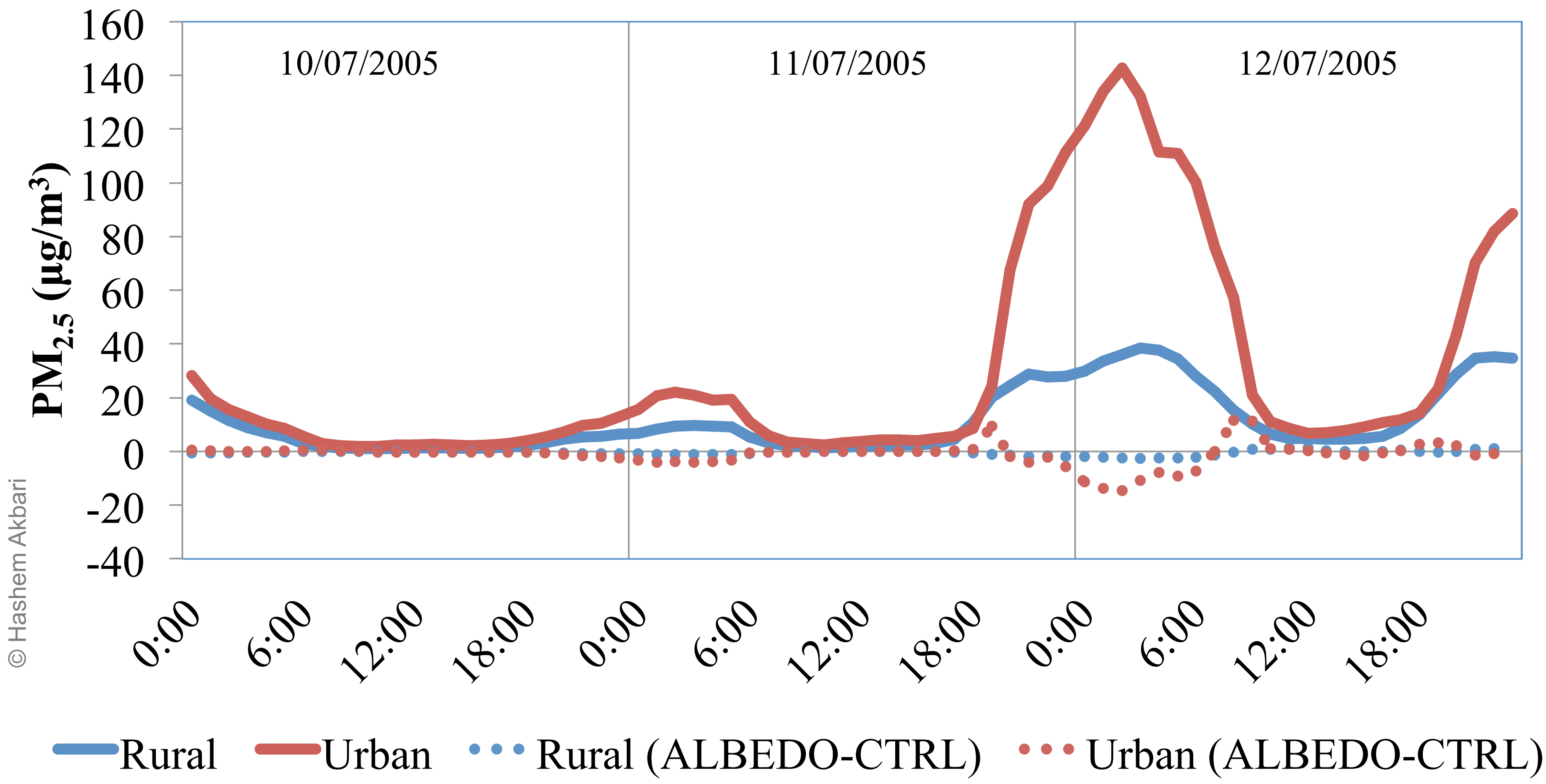
Energy consumption of HVAC systems (W/m²)



Ozone concentration (ppbv)



PM$_{2.5}$ concentration (μg/m^3)



Urban vegetation: Effects on energy and air-quality

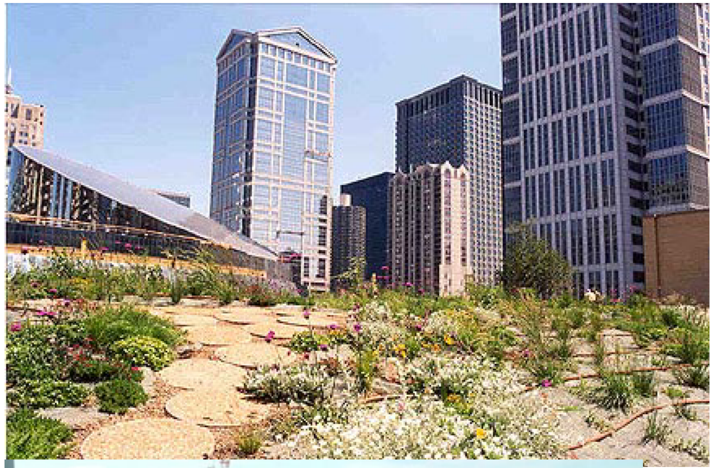
- Shading of buildings
- Evaporative cooling
- Wind shielding
- Smog reduction
- PM10 deposition
- Dry deposition
- Direct carbon sequestration

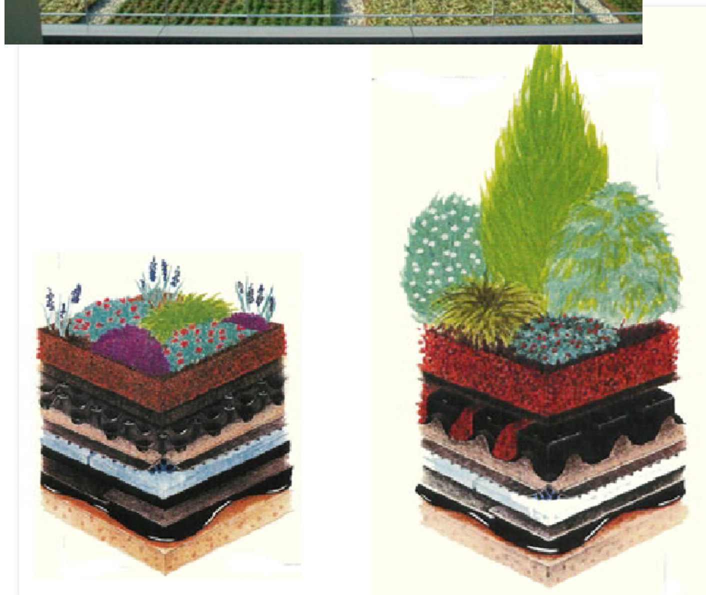
Other measures

- Roof gardens
- Green walls
- Anthropogenic heat reduction
- District cooling
- Outdoor evaporative cooling
- Energy efficient community design

Roof gardens

- Energy benefits similar to cool roofs
- Dirt on rooftops provides additional insulation: good for winter, not so good for summer
- Provides gardens to enjoy
- Design is complicated
- May cost significantly more than cool roofs
- Better suited for low-sloped roofs
- Potentially higher maintenance cost
- An expensive option in arid climates





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Cool surfaces also cool the globe

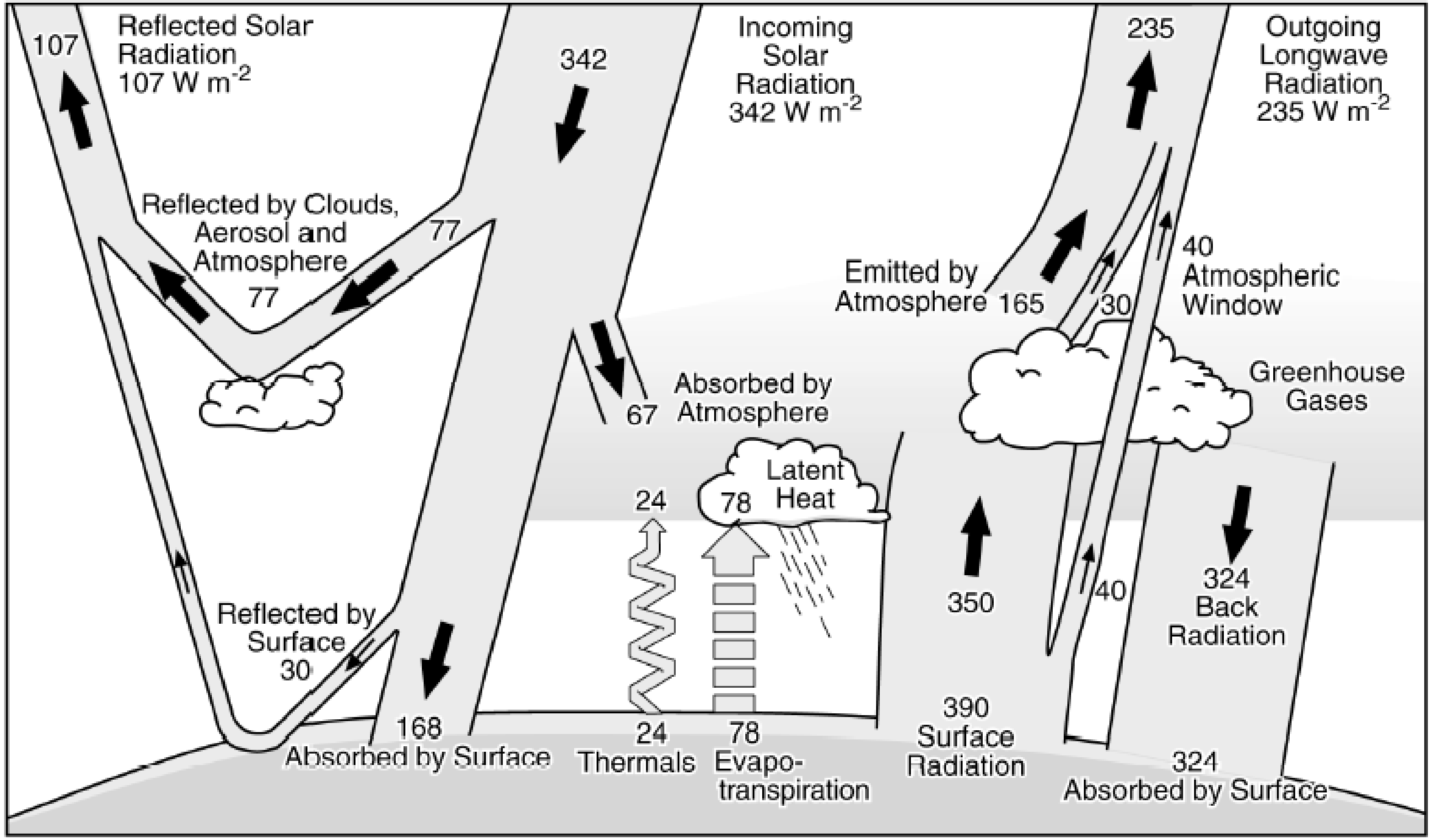
- Cool roofs, cool pavements, and shade trees save energy, improve air quality, and improve comfort; we estimate savings of > $50B/year
- Reflective roofs and pavements also directly cool the globe, independent of avoided CO_2

Geo-engineering 101

CO_2 offset: Methodology

- Changing albedo of urban surfaces and changing atmospheric CO_2 concentration both result in a change in radiative forcing (RF)
- Comparing these two radiative forcing relates changes in solar reflectance of urban surfaces to the changes in atmospheric CO_2 concentration

The Earth's radiation budget



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Source: Kiehl and Trenberth, 1997

Simulation model: University of Victoria Earth System Climate Model (UVic ESCM)

- An intermediate complexity global climate model which includes an interactive global carbon cycle.
- Atmospheric component of UVic ESCM is a vertically-integrated (2-D) atmospheric energy and moisture balance model, with specified wind fields that enable horizontal advection of heat and water
- Ocean is a 3-D general circulation model, coupled to a dynamic/ thermodynamic sea ice model
- Carbon cycle component includes dynamic vegetation on land, land carbon exchange via photosynthesis and decomposition, inorganic ocean carbon cycling, and ocean biological carbon uptake

Simulation model: University of Victoria Earth System Climate Model (UVic ESCM)

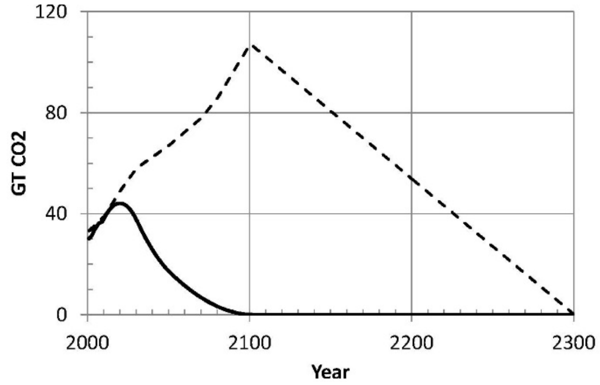
- As a computationally efficient global climate model, UVic ESCM is well suited to simulate the decadal- to centennial-scale climate response to greenhouse gas emissions, and has also been used as an effective tool to assess the climate response to solar radiation management
- Owing to the reduced complexity of the atmospheric component of the UVic ESCM, cloud feedbacks are not included, and the albedo of the atmosphere remains constant over time
- As a spatially-explicit model with reduced atmospheric variability, this model is well suited to assess the climate response of small and spatially-variable forcing associated with urban surface albedo modification.

Simulation scenarios

- Simulations began from a multi-thousand year spin up of the model under preindustrial conditions (zero anthropogenic forcing; CO_2 concentrations set to 280 ppm)
- We integrated the model forward to present day, driven by observed increases in atmospheric CO_2 concentrations
- After the year 2010, we allow atmospheric CO_2 concentrations in the model to vary interactively as a function of prescribed anthropogenic emissions, and simulated land and ocean carbon sinks.

Simulation scenarios

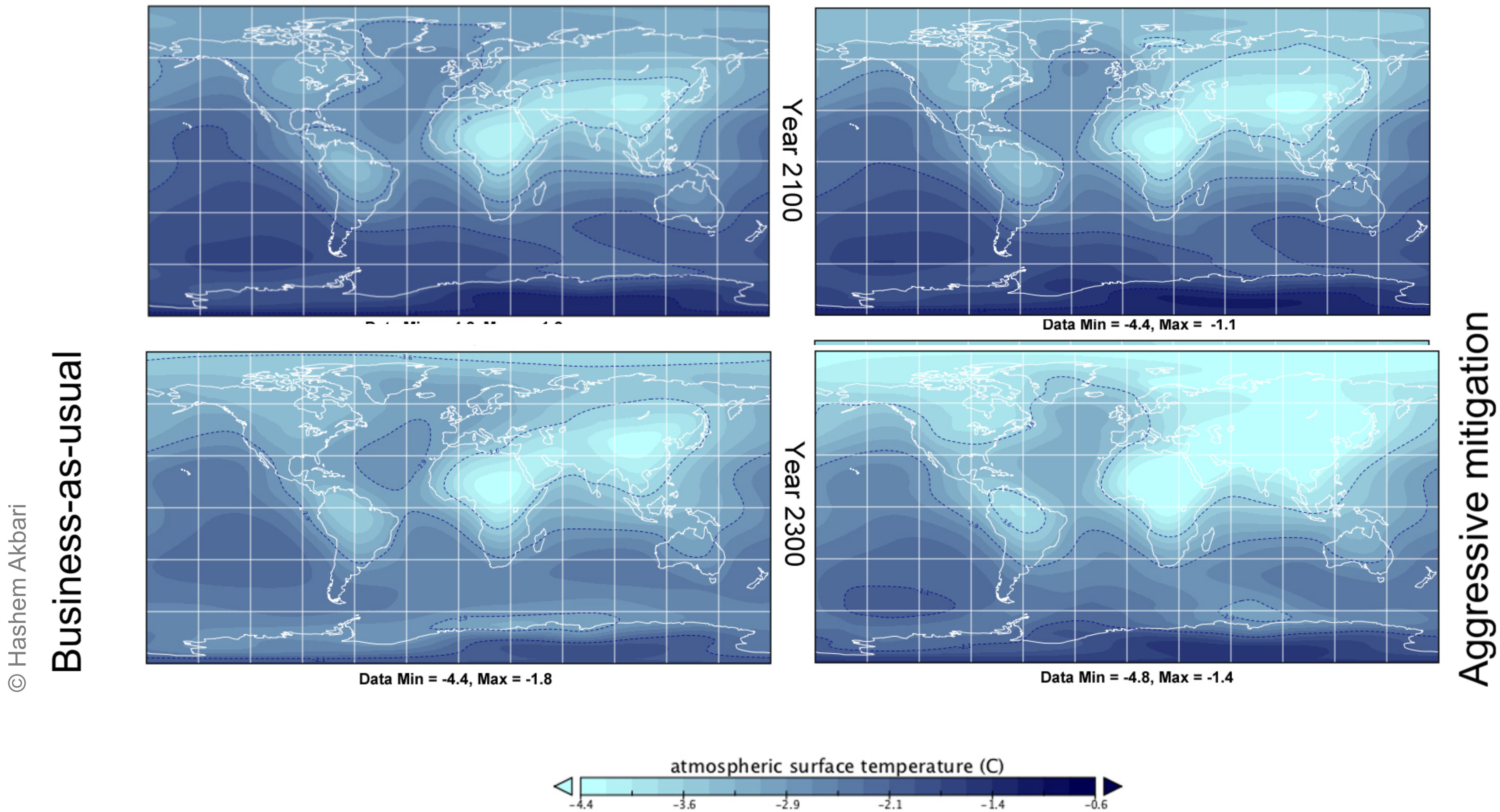
- For the period from 2010 to 2300, we used two CO_2 emission scenarios:
  - a "business-as-usual" (BAU) emission scenario, where CO_2 emissions increased dramatically to the year 2100, and then decreased linearly to zero at the year 2300 (resulting in total cumulative emissions of close to 5000 GtC or 18500 Gt CO_2)
  - an "aggressive mitigation" (AgMit) scenario, in which CO_2 emissions peaked around the year 2025 and decreased to zero at the year 2100 (resulting in total cumulative emission of 1000 GtC or 3700 Gt CO_2)



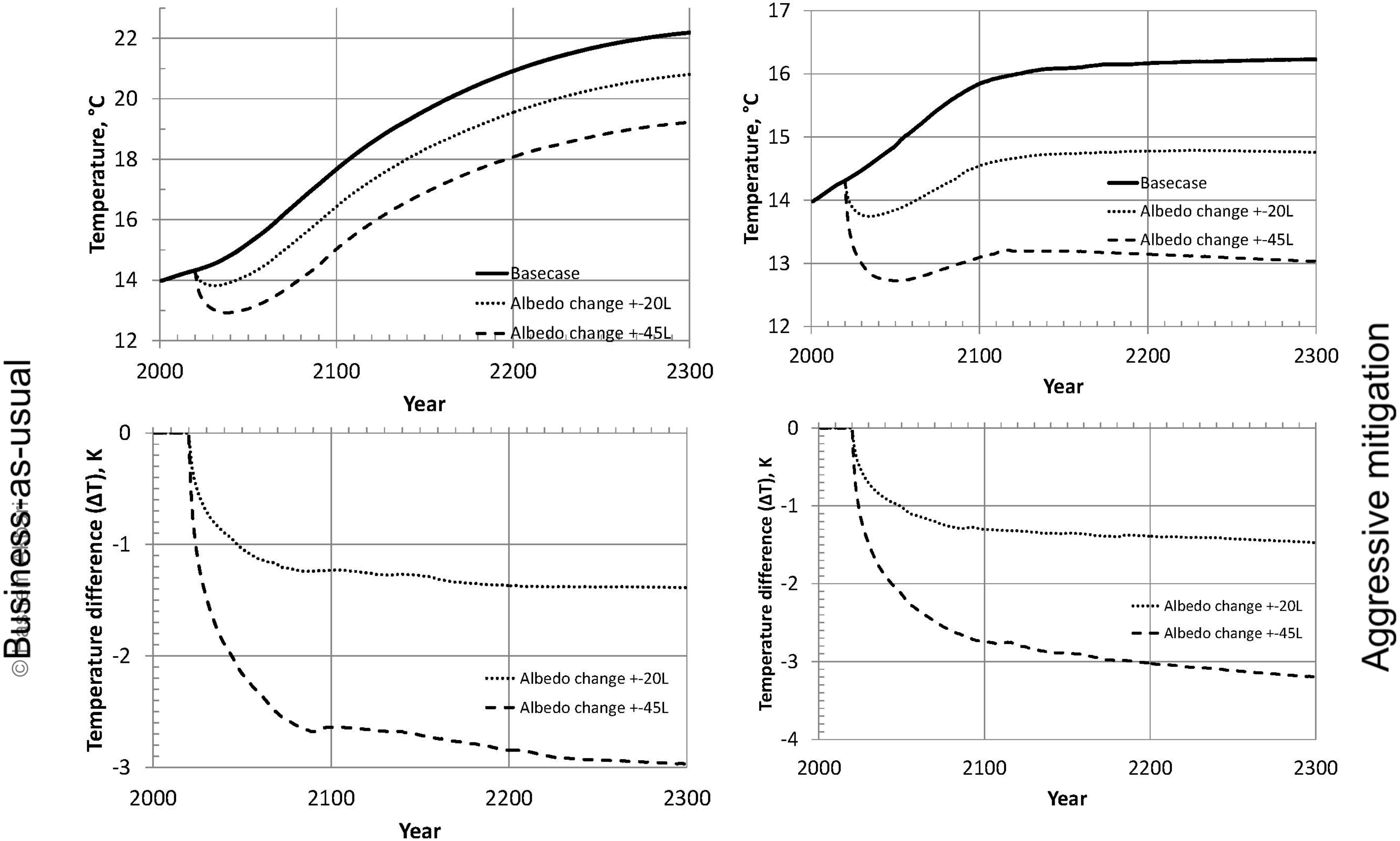
Simulation scenarios

- "Basecase" simulations: represent the climate response to these two CO_2 simulations in the absence of any land-surface albedo modification
- Albedo change simulations beginning at year 2010
  - "Case20": increased surface albedo by 0.1 over all land areas between ±20 latitude (26.5% of land area)
  - "Case 45": increased surface albedo by 0.1 over all land areas between ±45 latitude (61.9% of land area)
  - Urban areas: increased urban albedo by 0.1 using GRUMP and MODIS estimate of urban areas

Atmospheric surface temperature difference as a result of increasing the surface albedo of land areas by 0.1 between ± 45 degrees latitude

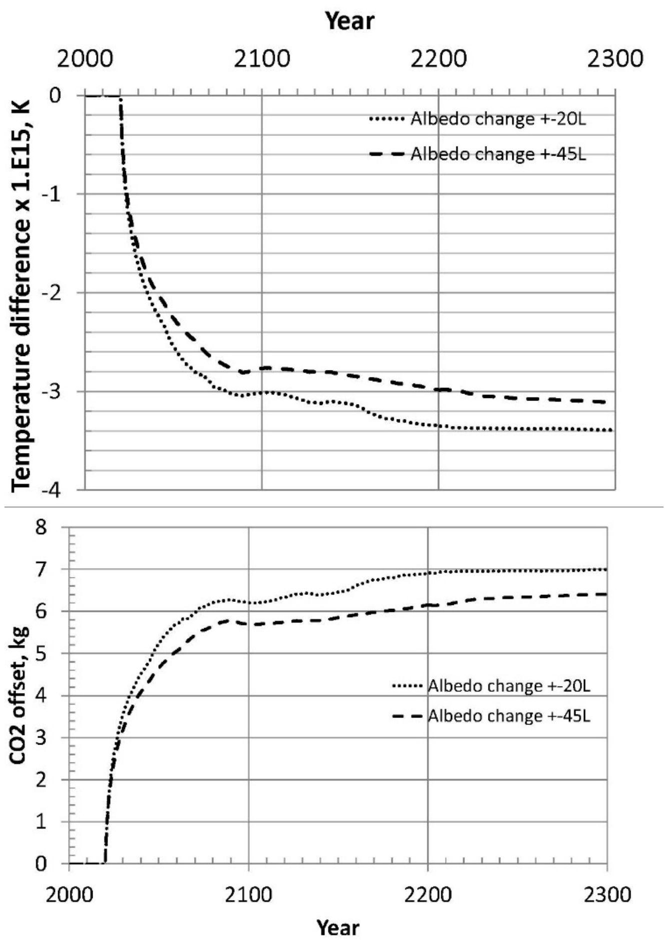


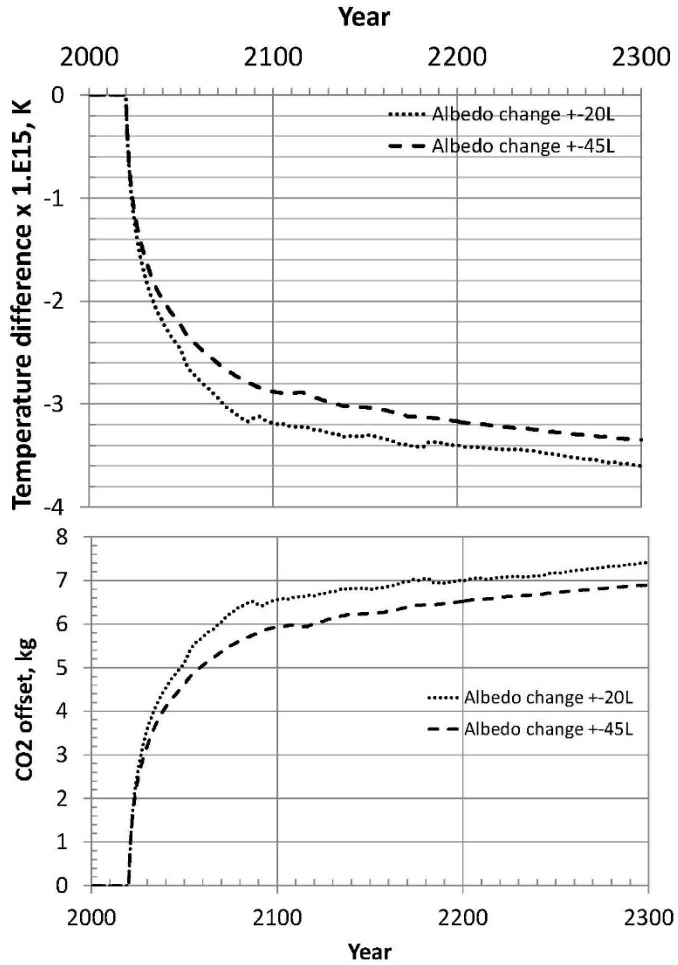
Global temperature change with increased surface albedo over land areas by 0.1 between ±20 degrees and ± 45 degrees



Global temperature change and equivalent CO_2 emissions offset per m^2 per albedo increase of 0.01

Business-as-usual

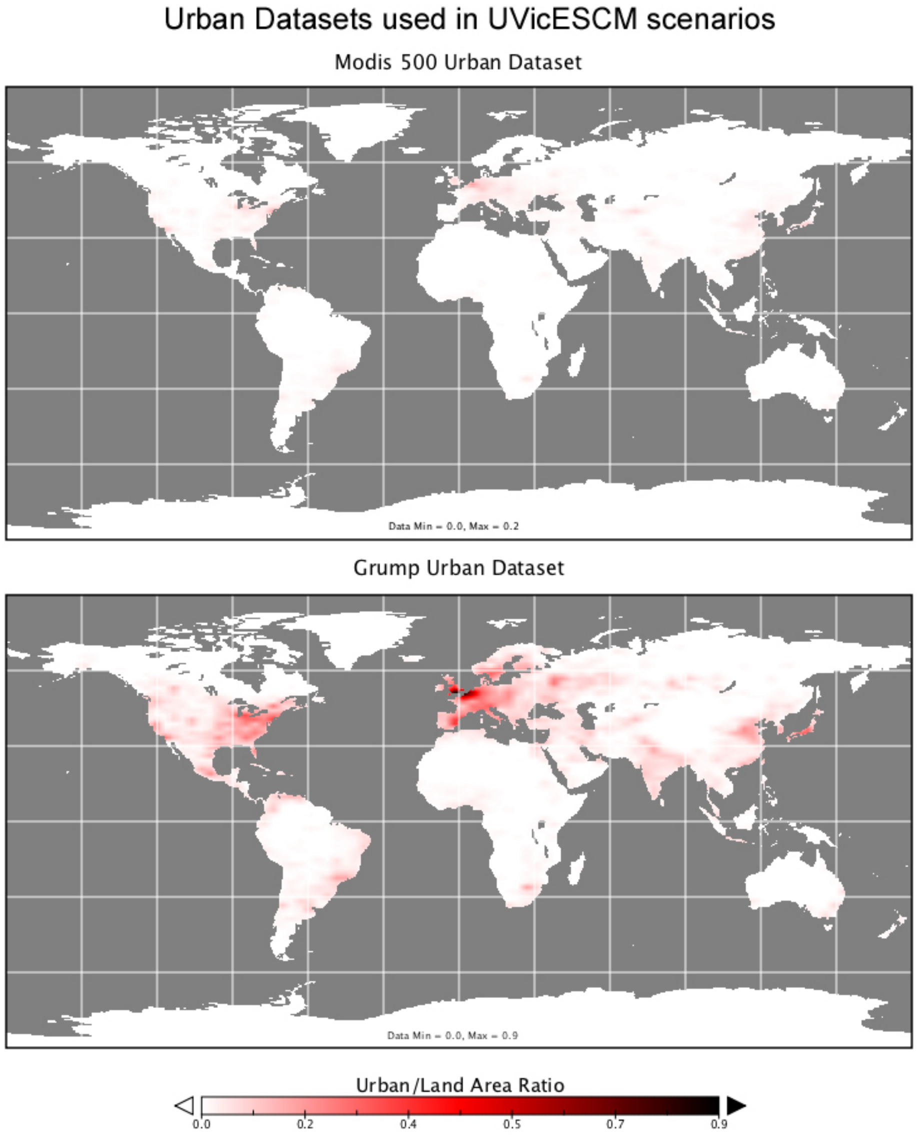




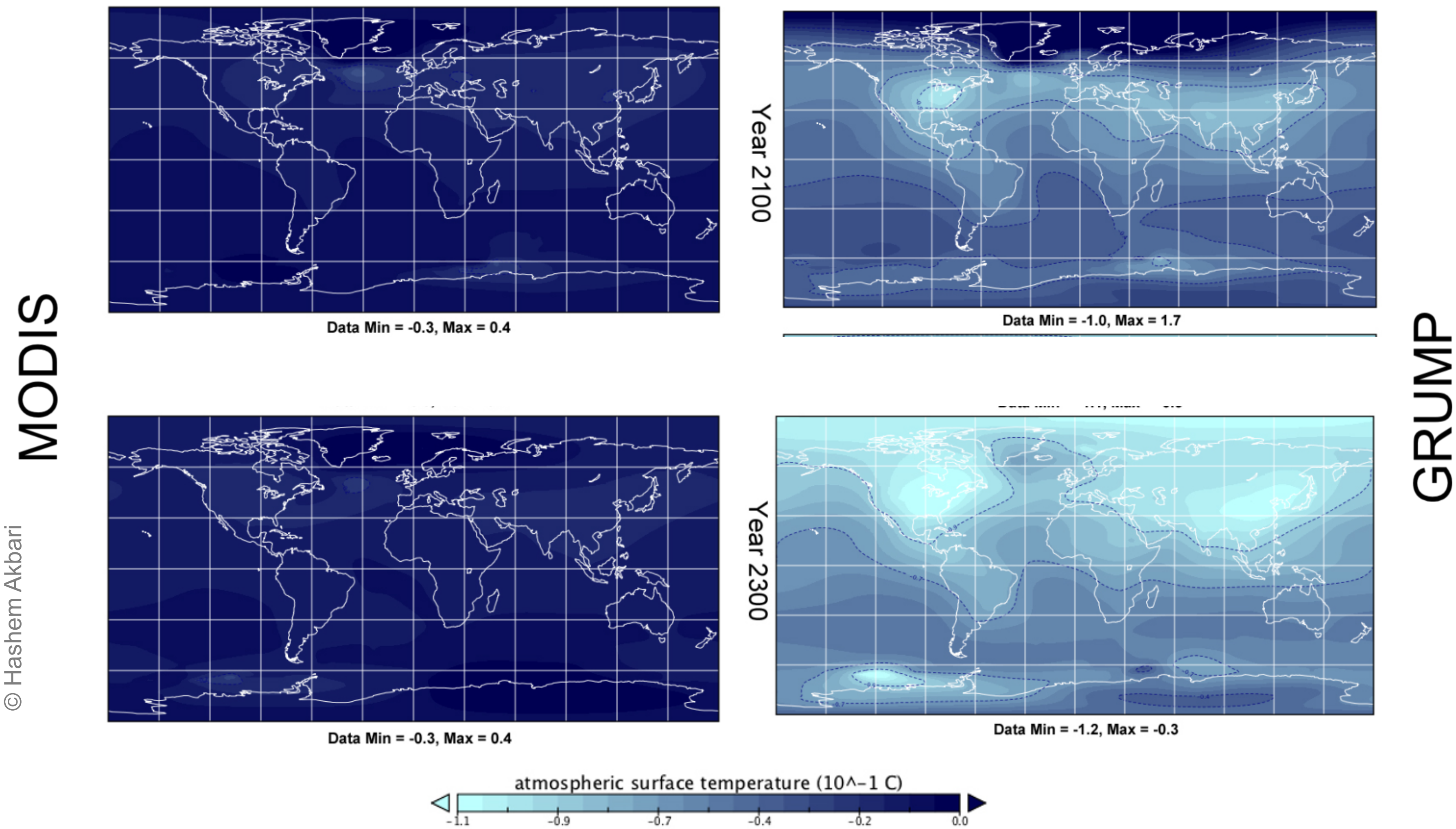
Aggressive mitigation

increasing albedo of 1 m^2 of a surface by 0.01 decreases the long-term global temperature by ~ $3x10^{-15}$ K, offsetting 6.5-7.5 kg of CO_2 emissions

MODIS and GRUMP datasets of urban areas



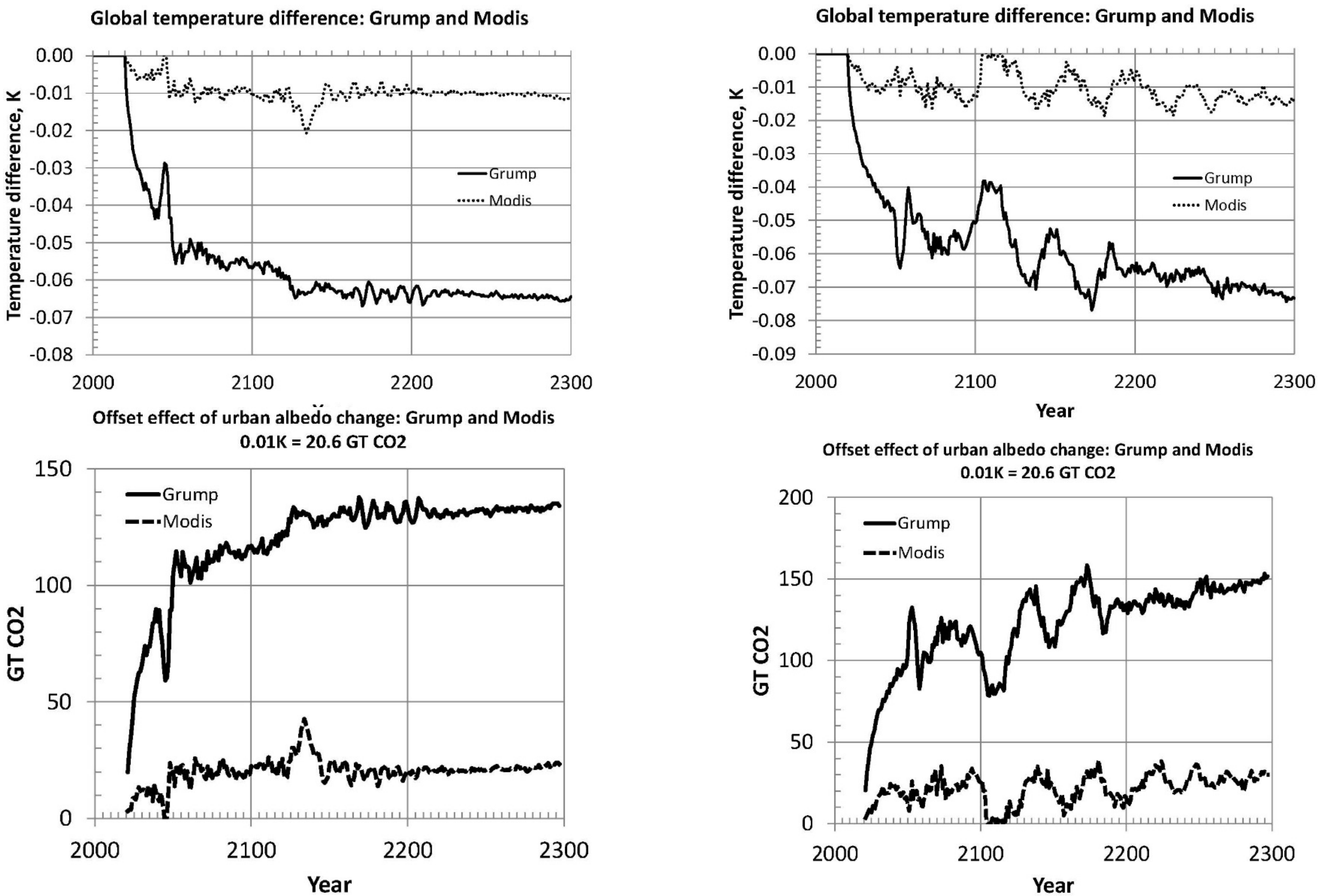
Atmospheric temperature difference by increasing albedo of urban areas by 0.1



Global temperature change and equivalent CO_2 emissions offset by changing the albedo of urban areas by 0.1

business-as-usual

aggressive mitigation



CO_2 offset of cool roofs and pavements

- Low-sloped roofs
  - Δ albedo for aged white roofs = 0.40
  - Emitted CO_2 offset for white roofs = -280 kg CO_2/m^2
  - It takes about 4 m^2 of white roof to offset 1 T CO_2 emitted
- Sloped roofs
  - Δ albedo for typical residential and non-residential cool roofs = 0.25
  - Emitted CO_2 offset for cool roofs = -170 kg CO_2/m^2
- Pavements
  - Δ albedo for cool pavement = 0.15
  - Emitted CO_2 offset for cool pavements = -100 kg CO_2/m^2

Source: Akbari et al, 2012

World-wide CO_2 offset of cool roofs and pavements

- Typical urban area is 25% roof and 35% paved surfaces
- World-wide urban areas = 1.5×10^{12} m^2 (1.5 M km^2)
- World-wide roof area = 3.8×10^{11} m^2 (0.38 M km^2)
- World-wide paved area = 5.3×10^{11} m^2 (0.53 M km^2)
- Emitted CO_2 offset for cool roofs = 67 GT CO_2
- Emitted CO_2 offset for cool pavements = 56 GT CO_2
- Total for cool roofs and cool pavements = 123 GT CO_2
- Note:
  - Akbari et al (2009) estimate 44 GT CO_2
  - Menon, Akbari et al (2010) estimate 57 GT CO_2
  - Akbari and Matthews (2010) estimate 78 GT CO_2
  - Akbari et al (2012) estimate 150 GT CO_2

CO_2 offset of cool roofs and pavements

- 44-150 GT CO_2 is over 1-4 years of the world 2025 emission of 37 GT CO_2
- At a growth rate of 1.5% in the world's CO_2 -equivalent emission rate, 44-150 GT CO_2 would offset the effect of the growth in CO_2-equivalent emissions for 11-25 years
- Would offset emissions from all cars for 18-60 years

Value of CO_2 offset

- CO_2 emissions currently trade at ~$25/tonne
- 44-150 GT worth $1100B-$3700B, for changing albedo of roofs and paved surfaces
- Cooler roofs also save air conditioning (and provide comfort) and improve air quality worth over $5000B over the next 100 years

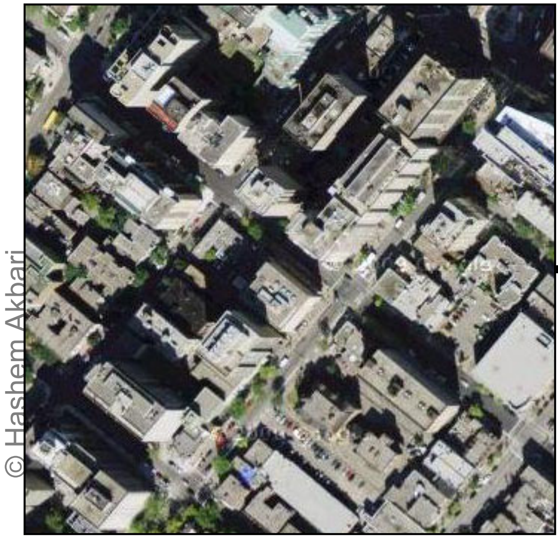
Comfort: ENVI-met simulations of Montreal

Step 1:

- Select the 300m*300m area
- Sketch the layout of buildings and trees
- Count floor numbers using 3D map

Step 2:

- Build 300m*300m domain with 3m*3m*3m resolution
- Defined each grid of building area, building height, soil, hard surface, and trees



Aerial satellite view

CAD map

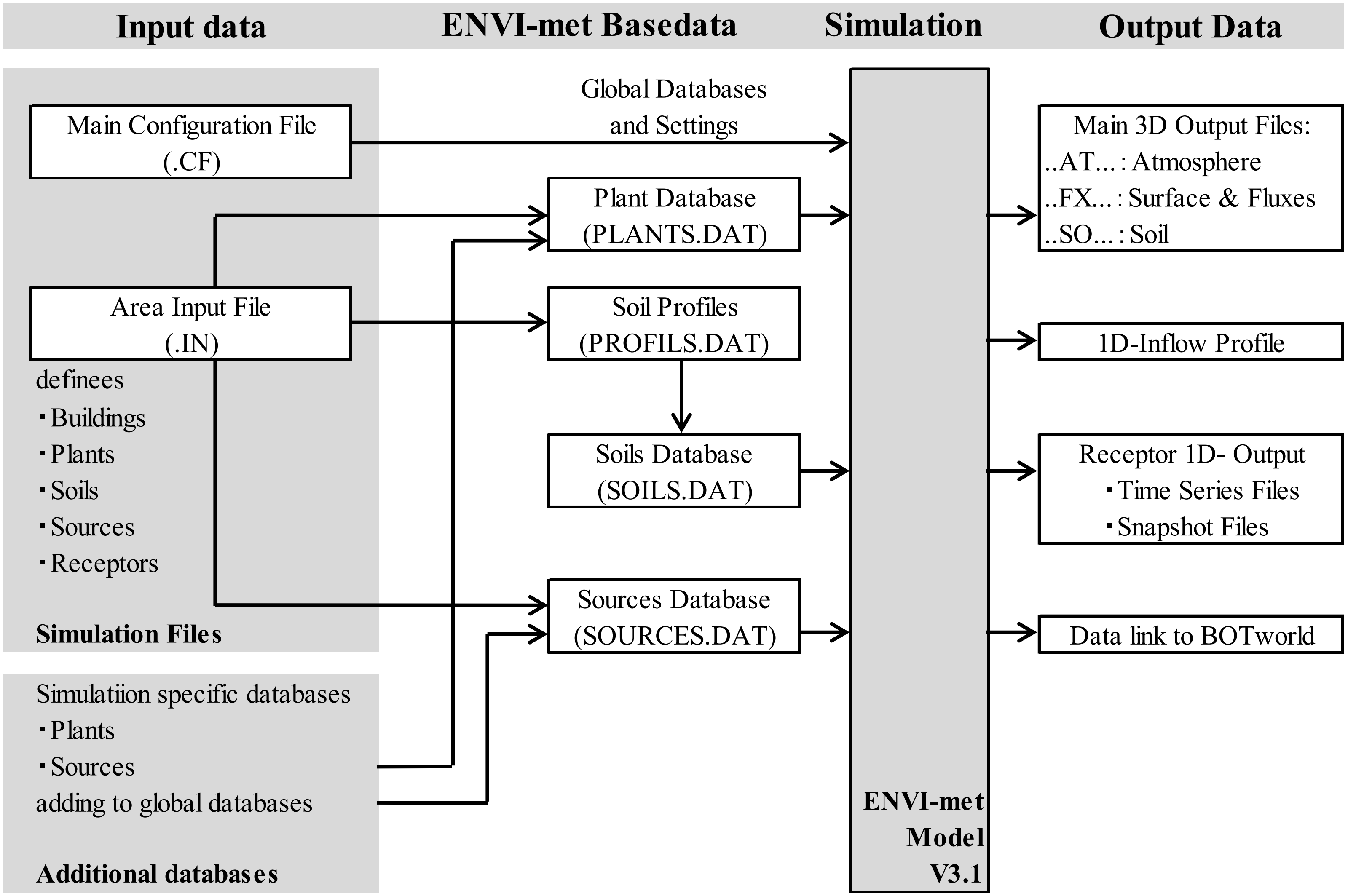
Area input file to the ENVI-met

Urban environmental simulation (ENVI-met)

- ENVI-met is a three-dimensional microclimate model designed to simulate the surface–plant–air interactions in urban environments.
- It has a typical spatial resolution of 0.5 to 10 m, and a temporal resolution of 10 s.
- A simulation is typically carried out for at least 6 h (usually for 24–48 h).
- The optimal time to start a simulation is at night or sunrise, so that the simulation can follow the atmospheric processes.
- Typical areas of application are Urban Climatology, Architecture, Building Design or Environmental Planning.

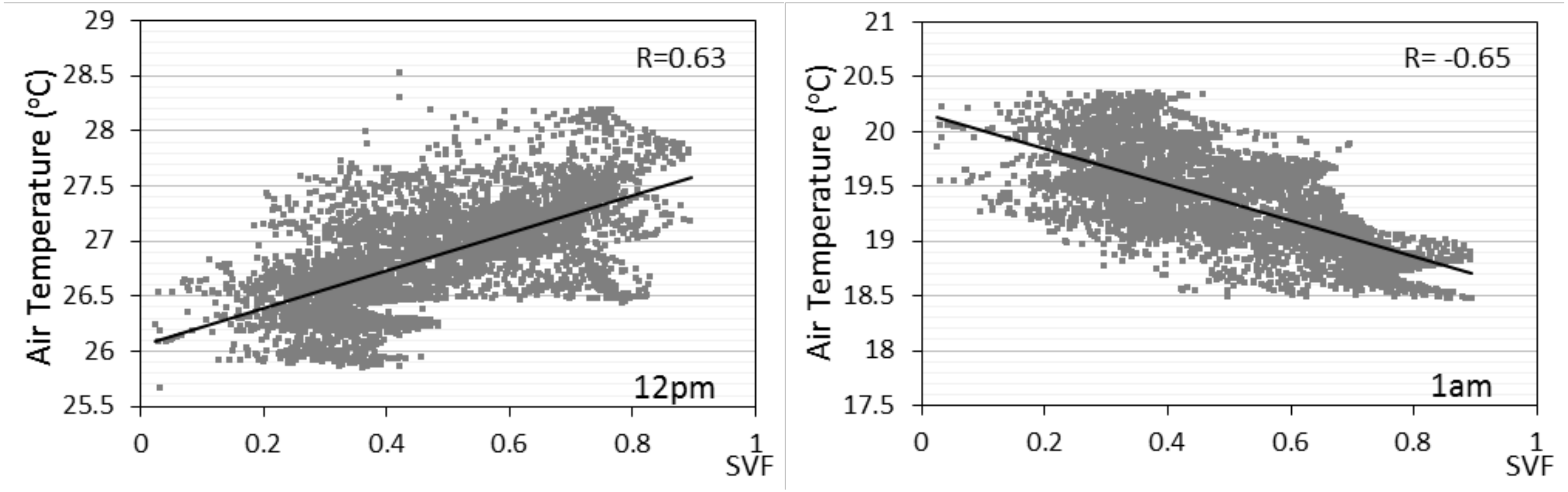
Source: http://www.envi-met.com/

Urban environmental simulation (ENVI-met)



Source: Data flow in ENVI-met V3.1 (http://www.envi-met.com/)

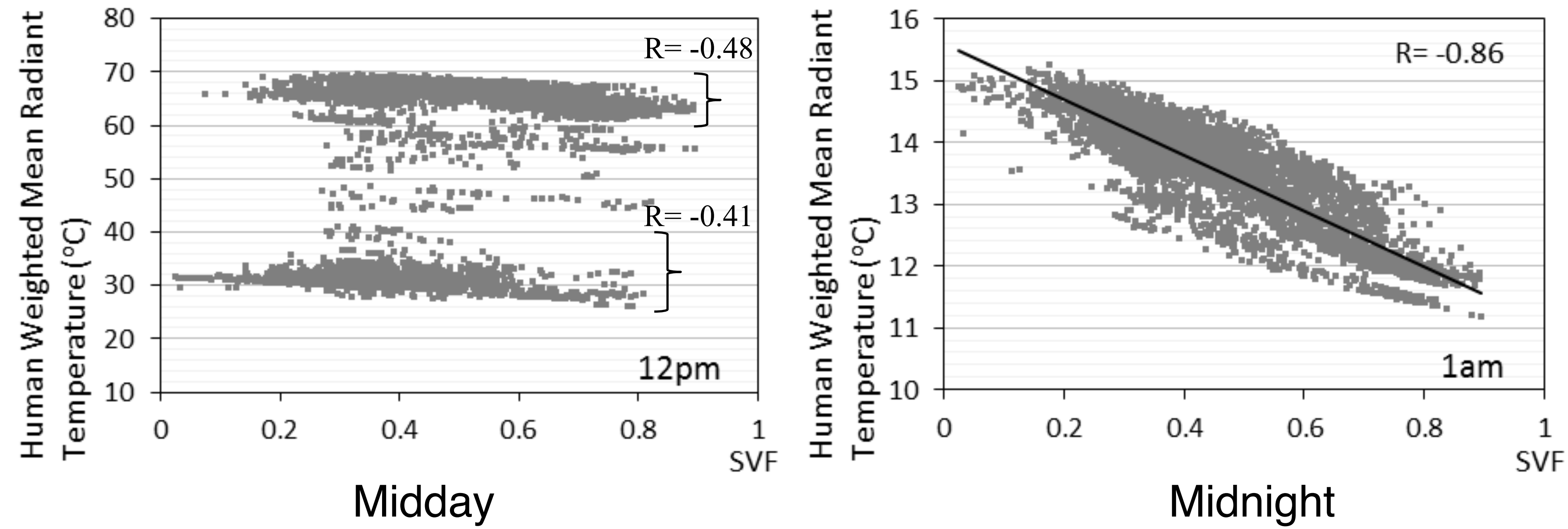
The effect of Sky View Factor



Midday Midnight

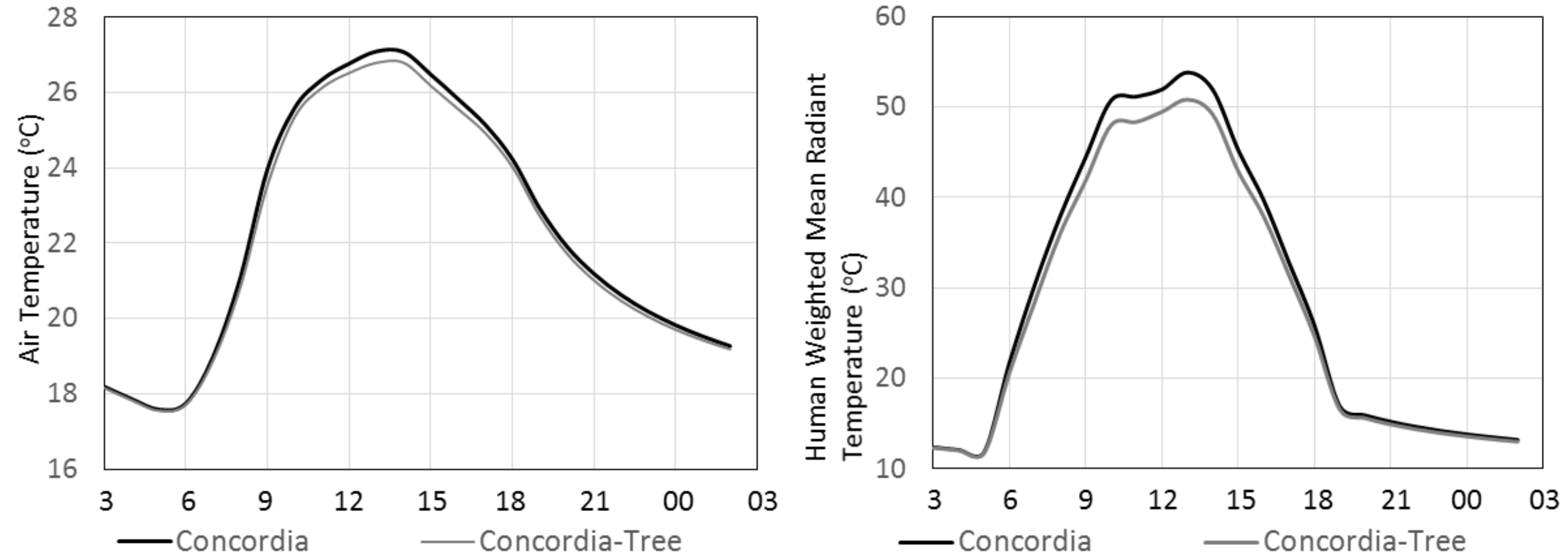
The effect of SVF (x-axis) on air temperature. The data is from the receptors at 1.5 m above the ground at noon (12 pm, 22 July) and 4 hours after sunset on a typical day in summer (1 am, 23 July). R=correlation coefficient.

The effect of Sky View Factor



The effect of SVF (x-axis) on mean radiant temperature. The data is from the receptors at 1.5 m above the ground at noon (12 pm, 22 July) and 4 hours after sunset on a typical day in summer (1 am, 23 July). R=correlation coefficient.

The effect of urban vegetation

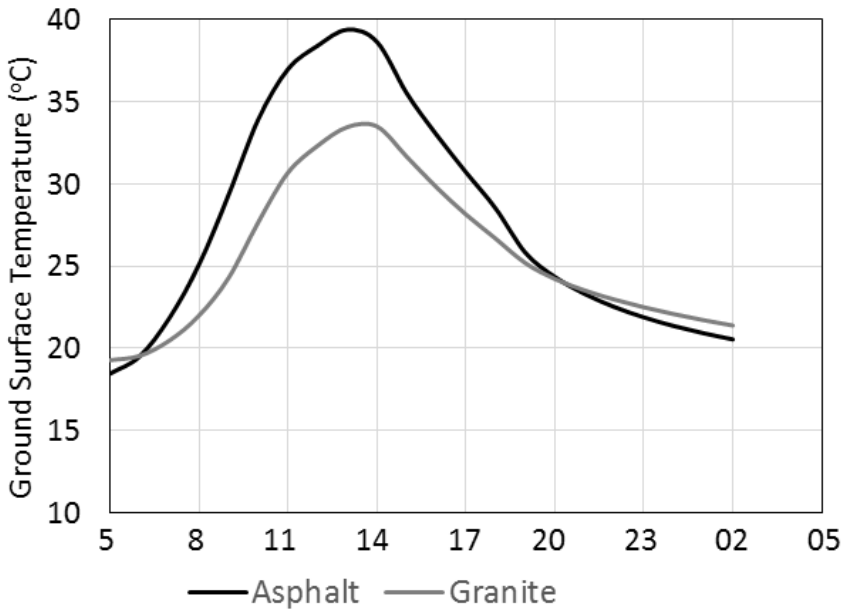


Comparison of environmental conditions at 1.5 m above the ground on a typical summer day (from 3 am, 22 July, to 2 am the next day)

Urban ground surface temperature

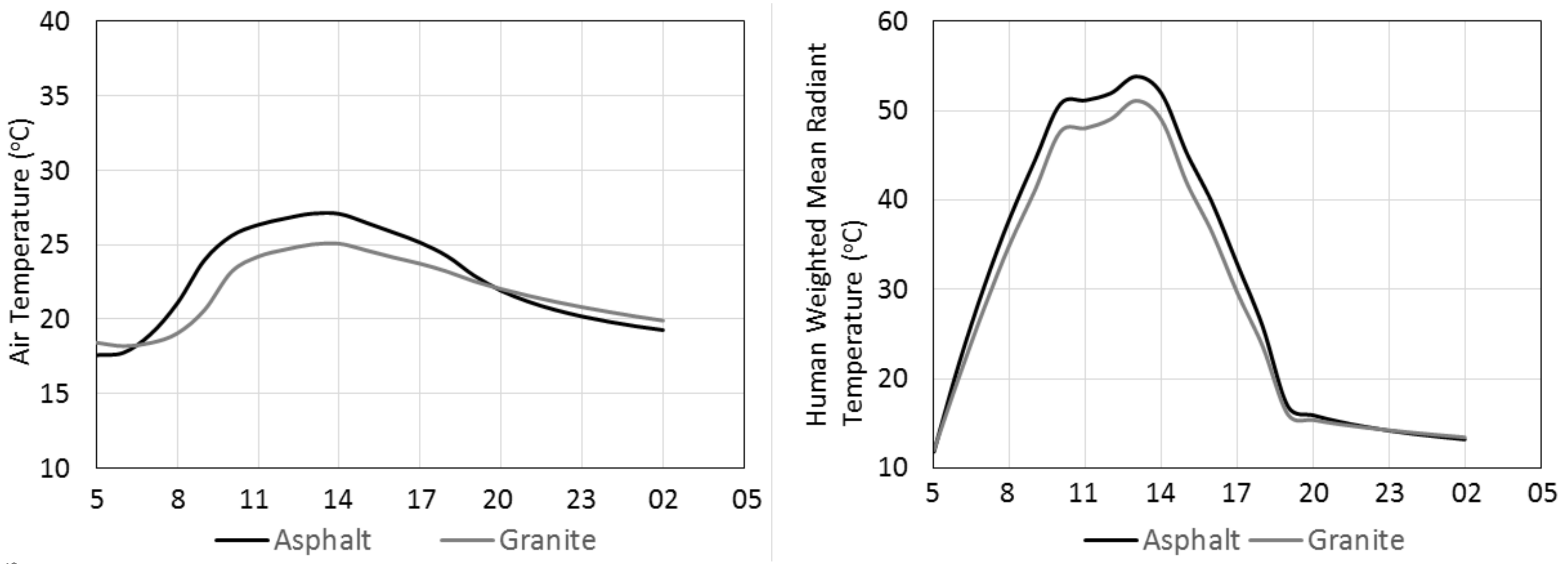
Details of ground surface materials

	Albedo	Heat Capacity [$Jm^{-3}K^{-1}$]*10^6	Heat Conductivity [$Wm^{-1}K^{-1}$]
Asphalt road	0.2	2.251	0.90
Granite pavement	0.4	2.345	4.61



Comparison of ground surface temperature on a typical summer day (from 5 am, 22 July, to 2 am the next day) with two ground surface materials.

The effect of urban ground surface



Comparison of environmental conditions at 1.5 m above the ground on a typical summer day with two ground surface materials

Case for France

White roofs in Corse; source: google

Case for France: Roofs

© Hashem Akbari

White roofs in Corse; source: google

Case for France: Pavements

White roofs in Corse; source: google

Modeling in support of policy: Research elements

- Perform detailed analysis (Energy and AQ effects)
  - Regional climate
  - AQ modelling: Pollution transport
- Develop detailed land use databases
- Develop implementation programs (roofs, pavements, trees)

Implementation focus

Tall buildings

- Cool roofs
  - Cool roofing materials
  - Roof gardens
- Cool walls
  - Green walls
  - Cool wall materials
  - Shades
- Cool pavements
- Urban parks?
- Street misters?

Low-rise buildings

- Cool roofs
  - Cool roofing materials
  - Roof gardens?
- Cool walls
  - Cool wall materials
  - Shades
  - Green walls?
- Shade trees
- Cool pavements

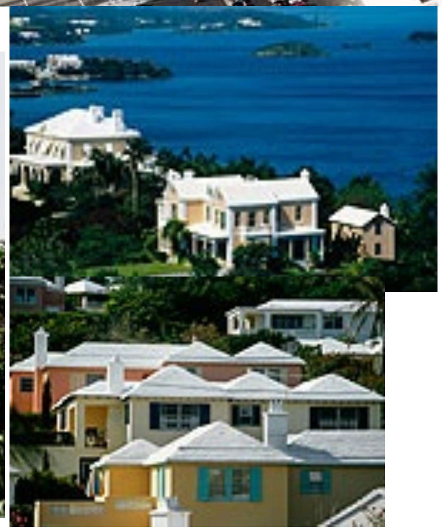
In place of conclusions

- Why modelling: In support of policy?
- What we know, what we do not know, and what we would like to know
- Modelling and measurements
- When have we done enough modelling?
- Still much to learn
- Applying what is learnt

Singapore conference 30 May to 1 June 2016

http://www.ic2uhi2016.org/

100m^2 of a white roof, replacing a dark roof, offset 10-20 tonnes of CO_2 emissions



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Thank You

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