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Seminar 17 - Hotter Cities, Hotter Climates: Modelling and Measuring Urban Heat Island Effects Around the World

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Cooling Hot Cities: A Systematic and Critical Review of the Numerical Modelling Literature

Learning objectives

1. Overview of current state of research into the effectiveness of key Urban Heat Island (UHI) mitigation techniques.
2. Understand the effect of the UHI on practical outcomes such as building energy consumption and outdoor thermal comfort.
3. Understand how the intensity of the UHI may vary between precincts and microclimates within a metropolitan area.
4. Understand how the time of daily maximum and minimum temperatures is delayed within an UHI.

Acknowledgements

I wish to thank numerous co-authors – colleagues and students, and especially co-authors of a paper titled:

"Cooling hot cities: A systematic and critical review of the numerical modelling literature", by E. Scott Krayenhoff, Ashley M. Broadbent, Lei Zhao, Matei Georgescu, Ariane Middel, James A. Voogt, Alberto Martilli, David J. Sailor and Evyatar Erell

Presentation outline

- Urban heat: brief historical overview
- Mitigation strategies
- Types of models
- Measuring cooling efficacy
- Meta-studies
- Limitations of tools
- Reducing air temperature – a silver bullet?

Global climate change and urban climate

*(Cerveny, 2009) **

"It is a popular opinion that the temperature of the winter season, in northern latitudes, has suffered a material change and become warmer in modern...times. This opinion has been adopted and maintained by many writers of reputation... indeed I know not whether any person, in this age, has ever questioned the fact..."

"By observations made in the city of New-York for 1 year, I found the mean temperature to be 53.5; but this is 1.5 degree too high; owing to an excess of heat within the city, beyond the general temperature of the climate.

The air in a city cools less at night, than in the country, and hence the morning observations were found to be too high. In many instances, ice as thick as glass was formed a mile from New-York, when an accurate thermometer in the city fell no lower than 40 deg."

** quoting Noah Webster, 1799*

Descriptive geography

(Howard, 1820)

"Mean Temperature of the Climate, … is strictly about 48.5F: but in the denser parts of the metropolis, the heat is raised, by the effect of the population and fires, to 50.50, and it must be proportionately affected in the suburban parts. The excess of the Temperature in the city varies through the year, being least in spring, and greatest in winter; and it belongs, in strictness, to the nights; which average three degrees and seven tenths warmer than in the country; while the heat of the day, owing without a doubt to the interception of a portion of the solar rays by a veil of smoke, falls, on a mean of the years, by about a third of a degree short of that in the open plain."

Phenomena:

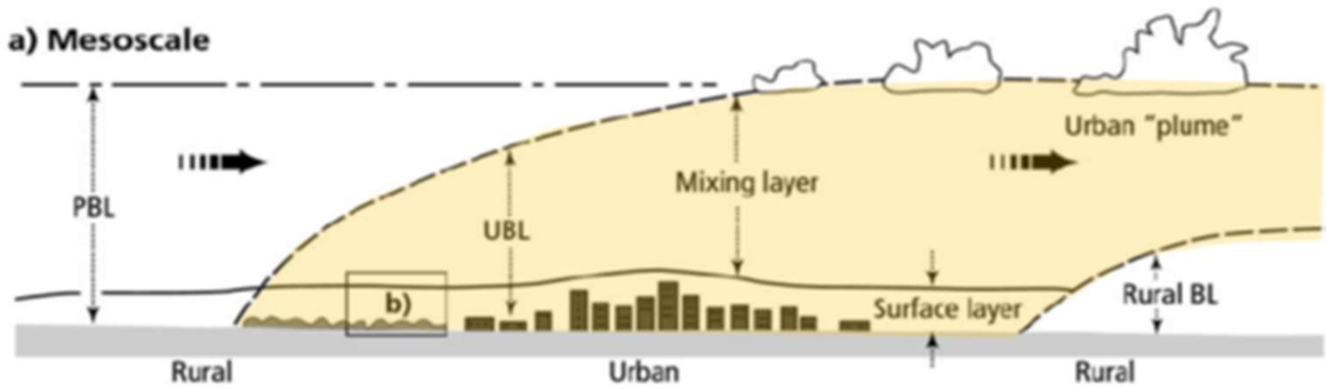
- Urban-rural difference
- Seasonal variations
- Diurnal pattern

Hypotheses:

- Related to density
- Anthropogenic heat
- Daytime interception of sunlight

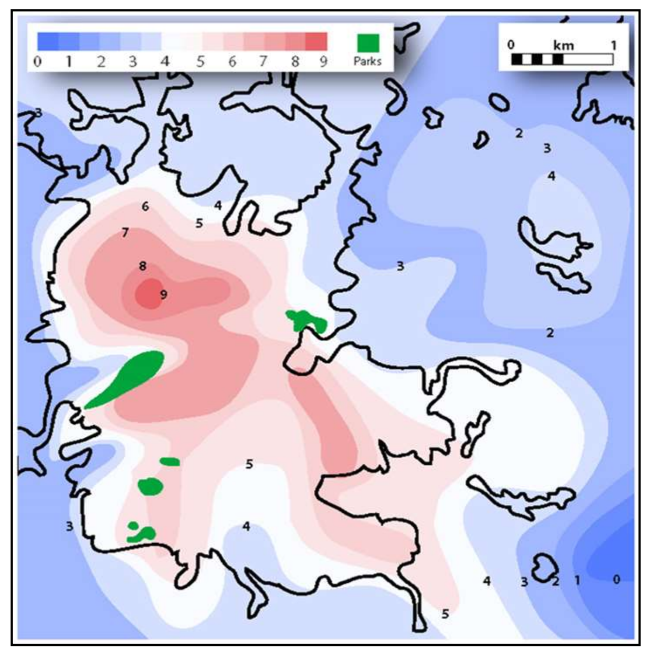
Types of UHI

The boundary layer heat island (BLHI)



A surface heat island (SHI)

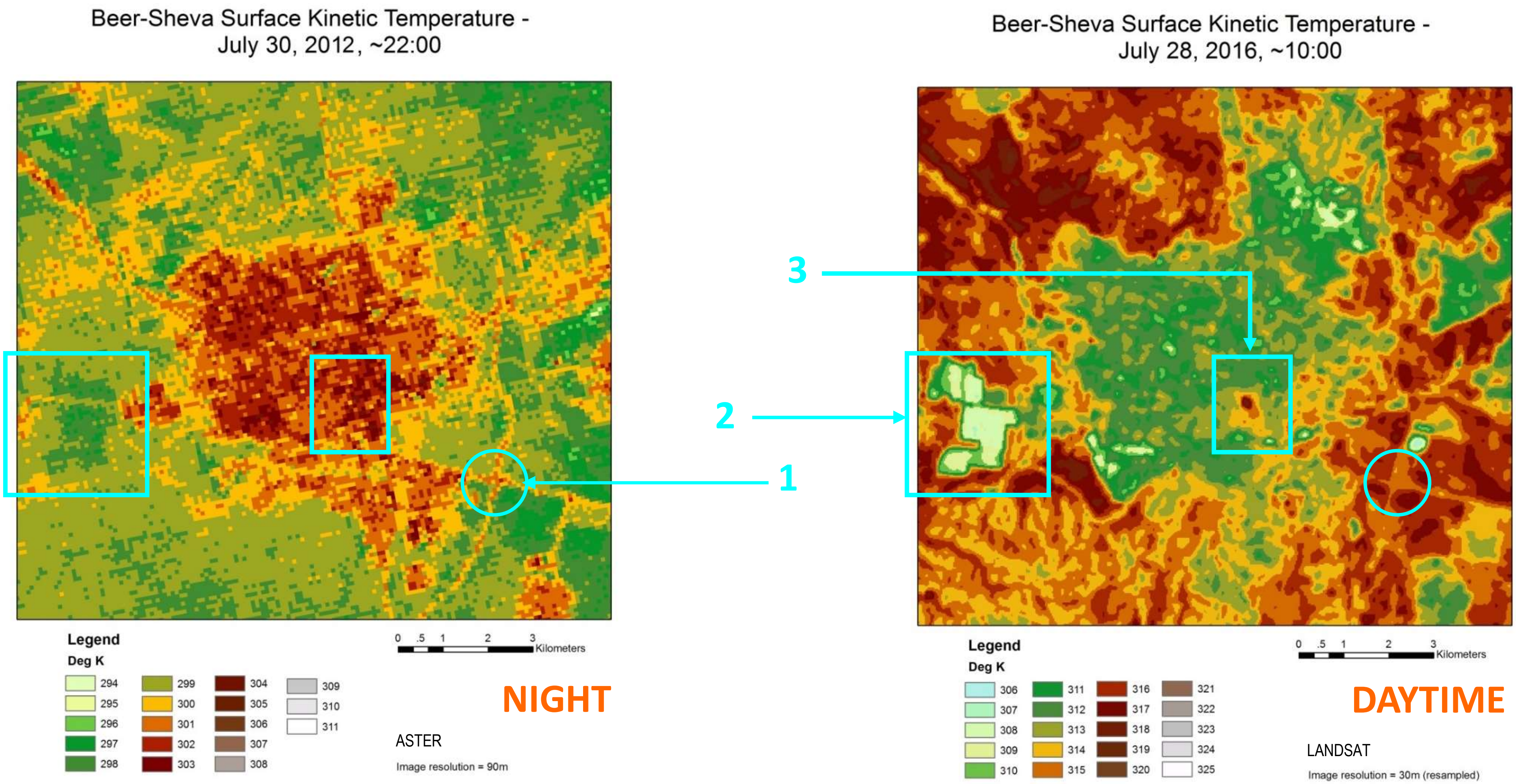
The canopy layer heat island (CLHI)



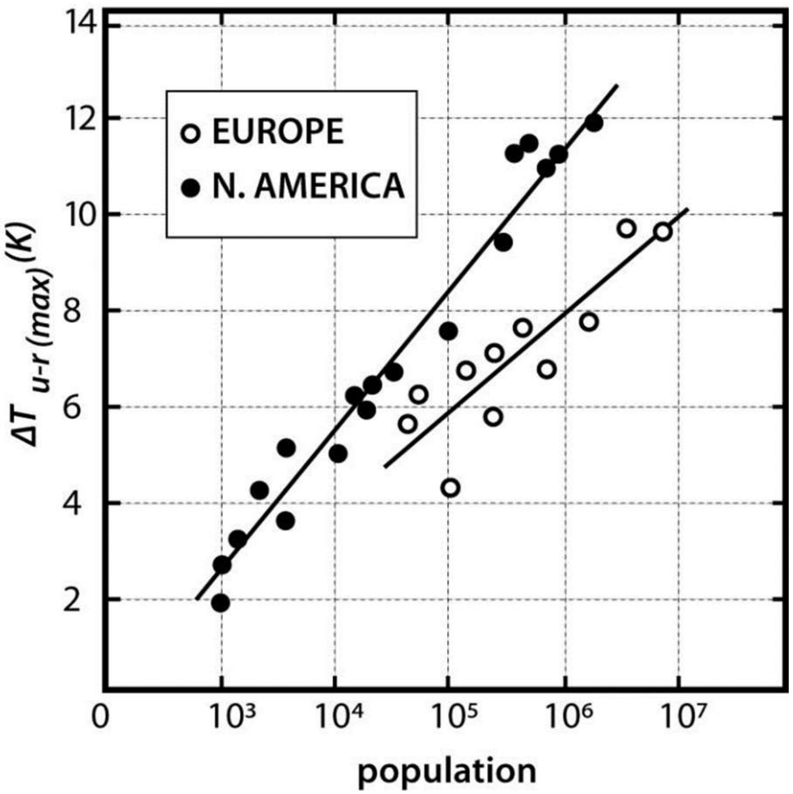
Spatial and temporal variations of the surface heat island

(Image analysis of Be’er Sheva by Shai Kaplan)

1. asphalt road cooler than bare soil
2. cool irrigated fields
3. cemetery (no vegetation)

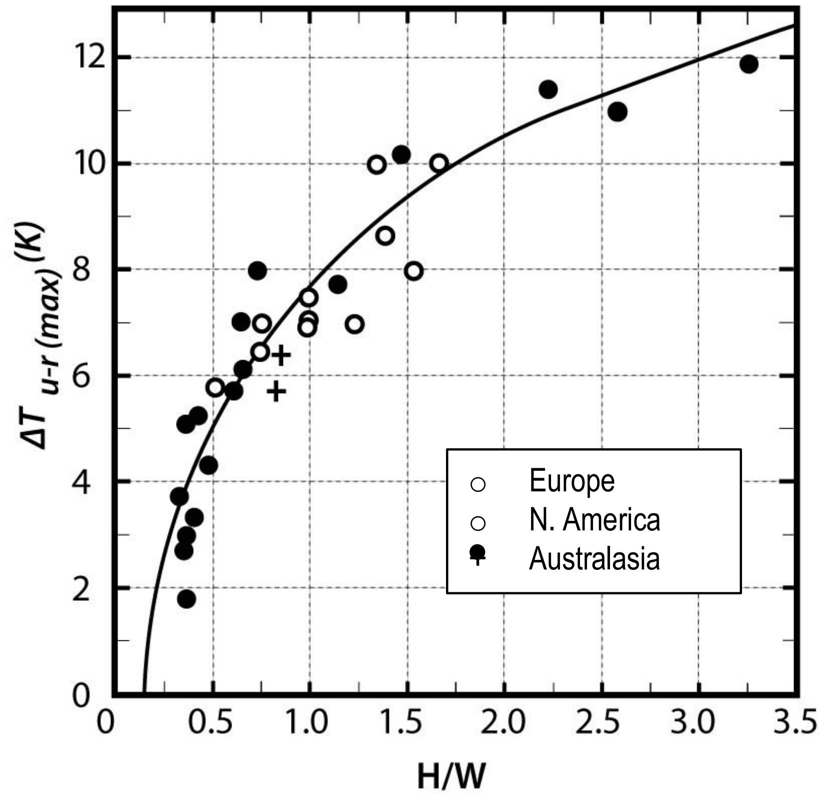


Intensity of canopy layer heat island



Relation between maximum observed heat island intensity and the population of North American and European cities.

(Redrawn from Oke, 1973)

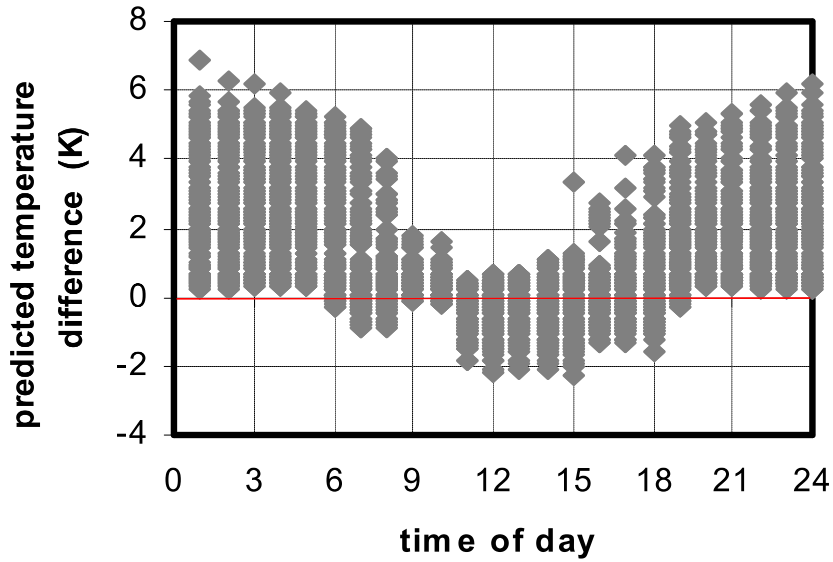


Relation between maximum observed heat island intensity and the height-to-width ratio of a sample of street canyons at the centre of 31 cities.

(Redrawn from Oke, 1987)

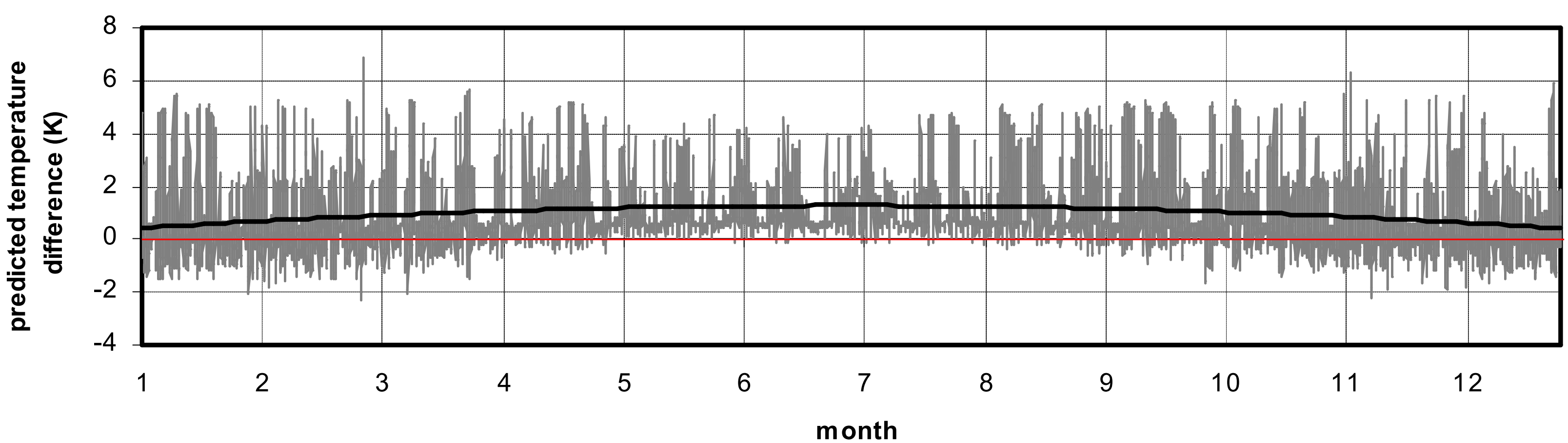
Simulated diurnal and seasonal patterns of CLHI

(Erell and Williamson, 2007)



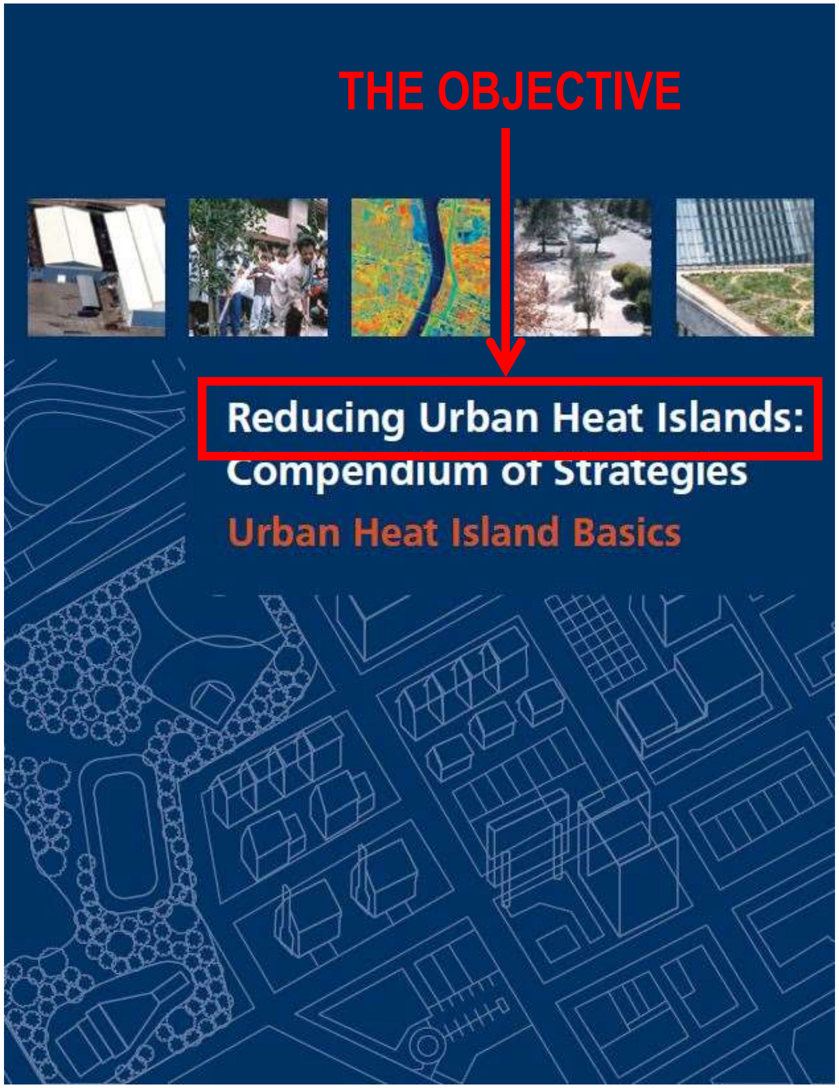
Modeled canyon heat island intensity (based on Australian BoM data for 1987):

- ❑ Nocturnal heat island with modest daytime cool island
- ❑ Canyon heat island is stronger in winter



Heat mitigation strategies

(U.S. EPA, 2012)



What works best for reducing the hazards of climate extremes such as heat waves in the cities we work in?

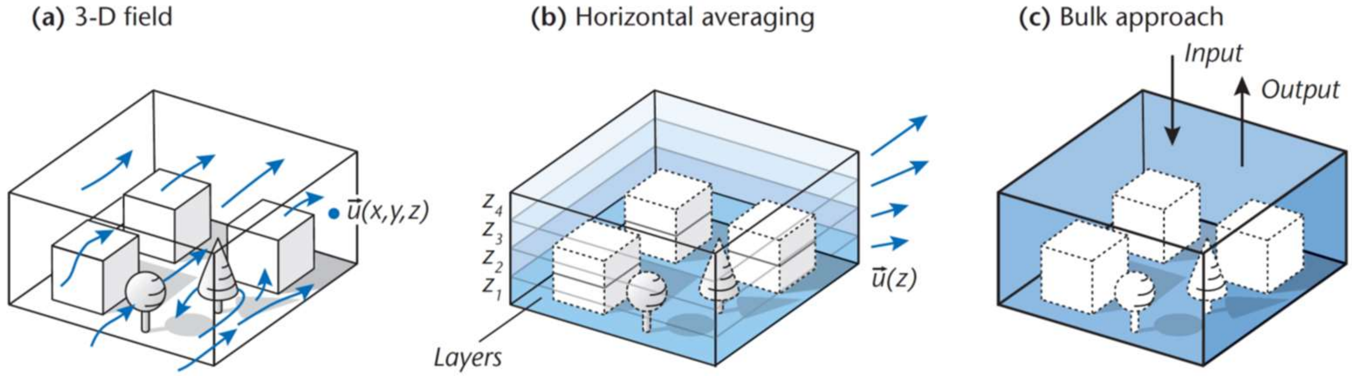
Cool roofs
- High albedo
- green

Cool paving
- High albedo
- Porous + water evaporation

Vegetation
- Parks
- Localized trees
- Surface cover (grass, cover plants)

Shading

Numerical models of the urban climate



Common numerical model conceptualizations of the urban canopy, with increasingly detailed physical representation and computational expense from right to left (Reproduction of Fig. 2.16 of Urban Climates, by Oke et al. 2017).

COMPLEXITY

(Oke et al, 2017)

MESO-SCALE (nested x3)

Weather Research and Forecasting model (WRF)
+ Building Energy Model (BEM)
+ Building Effect Parameterization (BEP)

LOCAL SCALE

- Town Energy Balance (TEB)
- Urban Weather Generator (UWG)
- Canyon Air Temperature (CAT)

MICRO SCALE

- ENVI-met

SCALE

A meta-study: Assessing the papers

(Krayenhoff et al, 2020)

Meta-data reporting

1) Site metadata are provided;
2) Forcing meteorology is characterized;
3) Heat mitigation implementation metadata are provided;
4) Air temperature is specified spatially and temporally.

Model

5) Model accurately represents relevant physical processes;
6) Model evaluation is appropriately targeted and successful;
7) Model application is sound.

Search results: 2,414 papers; 146 papers met all criteria; only 47 studies were high quality

Albedo Cooling Effectiveness (ACE)

(Krayenhoff et al, 2020)

$$ACE = -\frac{\Delta T}{\Delta \alpha_N} = -\frac{\Delta T}{\Delta \alpha_s \cdot \lambda_s}$$

ACE	Albedo Cooling Effectiveness
ΔT	the change in air temperature
$\Delta \alpha_N$	is the neighborhood scale, plan area-averaged change in albedo
$\Delta \alpha_s$	is the change in albedo of the modified surface
λ_s	is the area of modified surface divided by the corresponding overall horizontal plan area

The ACE value in degrees Celsius represents the cooling obtained from a neighborhood albedo increase from 0.0 to 1.0.

Vegetation Cooling Effectiveness (ACE)

(Krayenhoff et al, 2020)

$$VCE = -\frac{\Delta T}{\lambda_s}$$

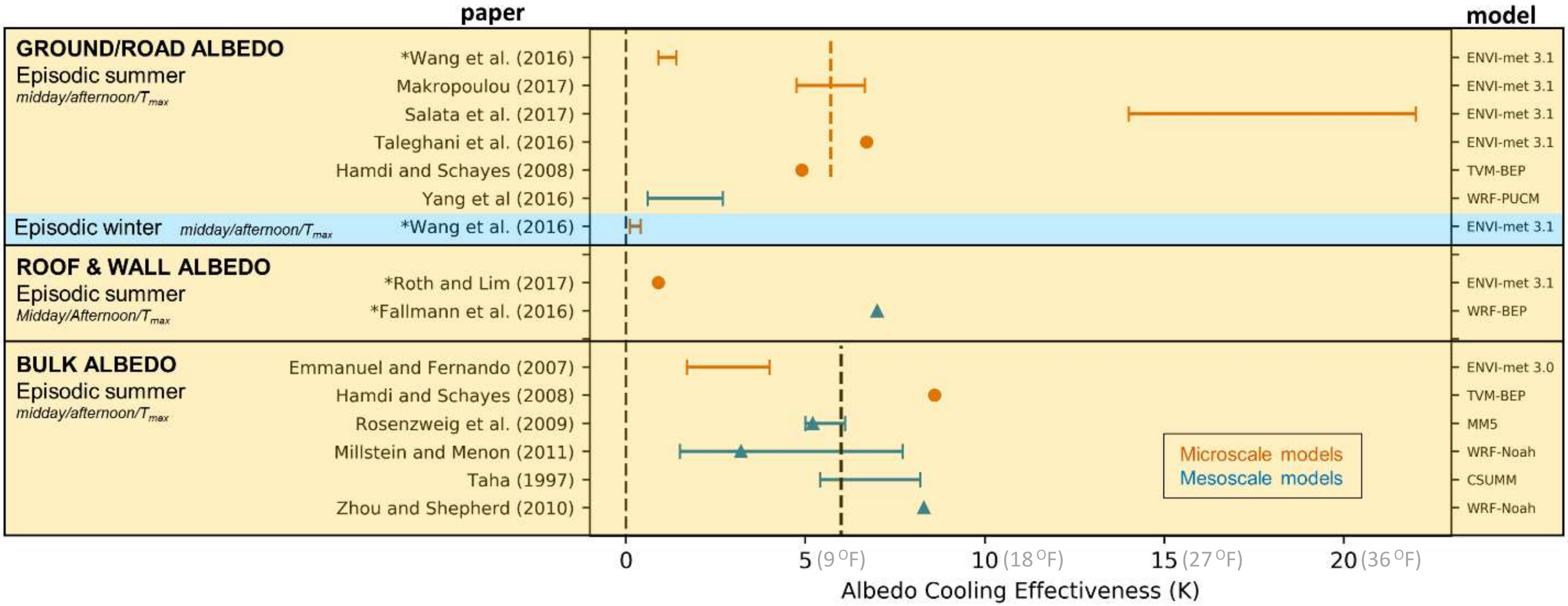
VCE	Vegetation Cooling Effectiveness
ΔT	change in air temperature
λ_s	the added surface area of vegetation divided by the associated plan area

The index does not include a measure of 'intensity' (analogous to change in albedo), although plants differ in effect due to

- shading vs. non-shading
- leaf area index (LAI)
- plant metabolism (e.g. succulents vs needle vs broad leaf
- water availability

Albedo cooling effectiveness (i) ground, building walls

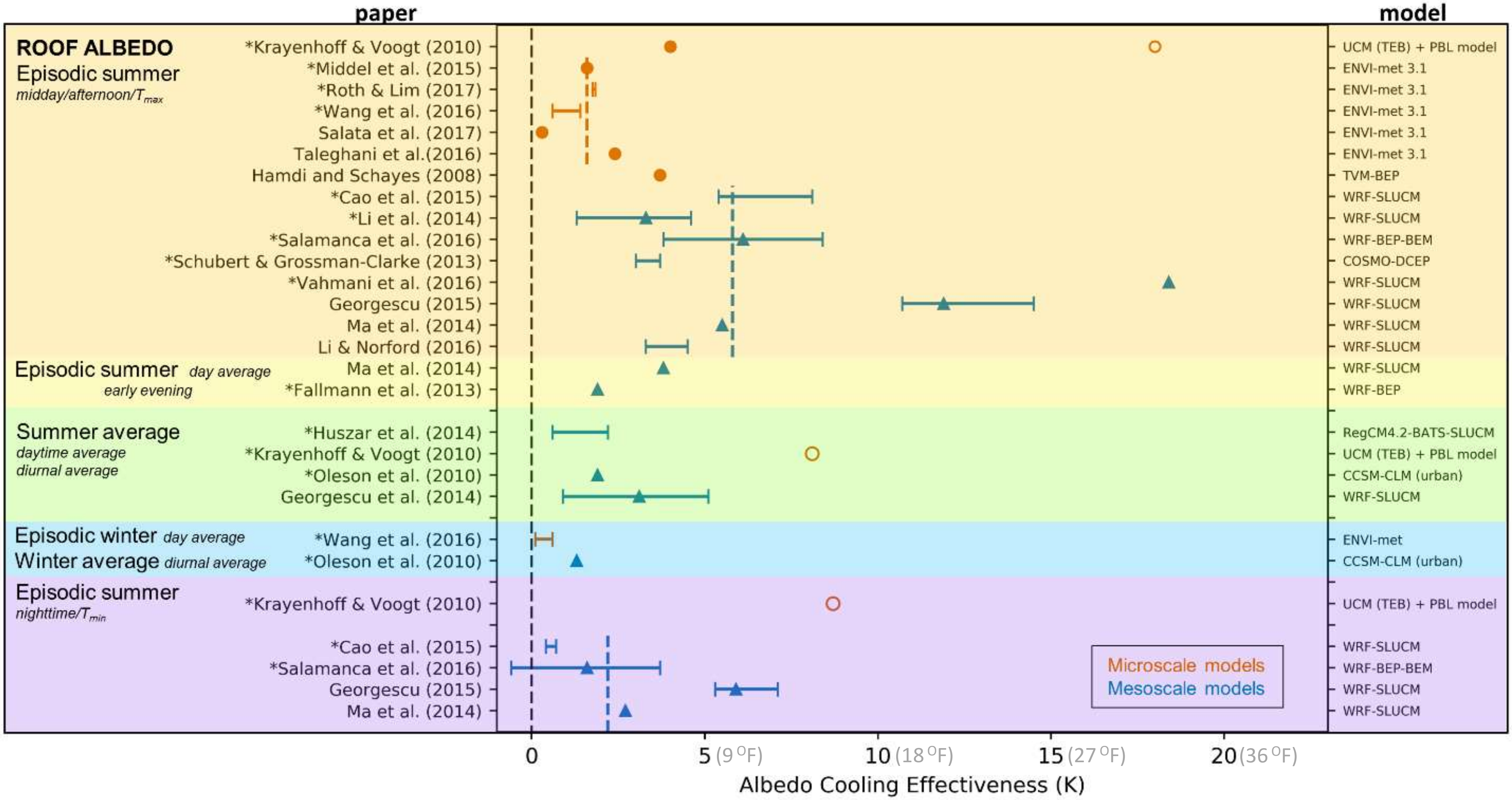
(Krayenhoff et al, 2020)



Albedo cooling effectiveness (*ACE*) from roof (a) and other (b) albedo implementations for two model scales and across several seasons and approximate times of day. Solid horizontal lines corresponding to each study indicate maximum and minimum reported *ACE* within a study, and symbols indicate median *ACE* (where appropriate). Vertical, coloured dashed lines indicate median *ACE* for summer afternoon ENVI-met 3.1 (orange) and mesoscale (green) study results, for summer nighttime mesoscale results (blue), and combined micro/mesoscale uniform or bulk albedo results (black). Highest values reported by Krayenhoff and Voogt (2010) in each category are for a 'no advection' case, and represent an estimate of maximum potential *ACE* (open circles). Articles indicated by a "*" met all six conditions outlined in Sect. 2.5. The "bulk albedo" section combines bulk treatments of the urban surface (mesoscale) and uniform treatment across all facets (microscale).

Albedo cooling effectiveness (ii) roof

(Krayenhoff et al, 2020)



Vegetation cooling effectiveness (i) trees

(Krayenhoff et al, 2020)

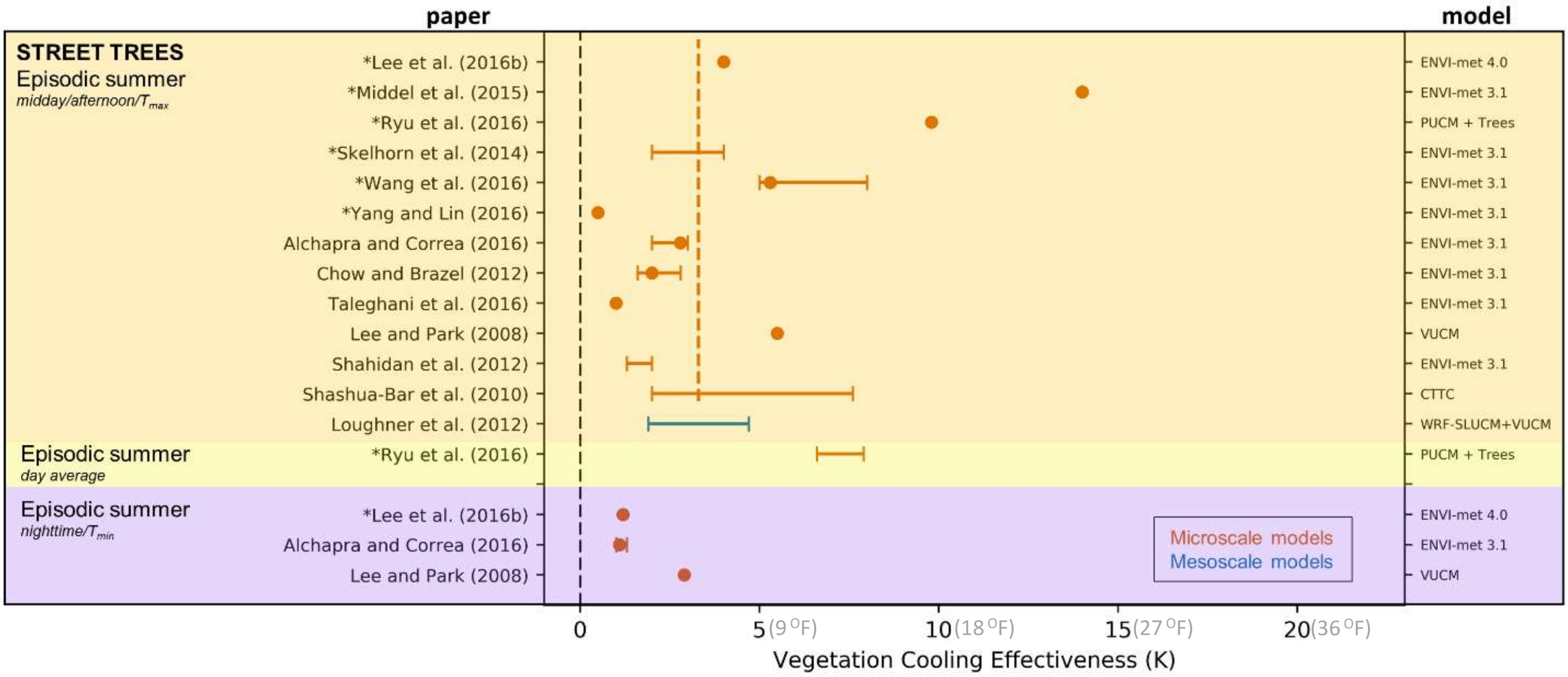
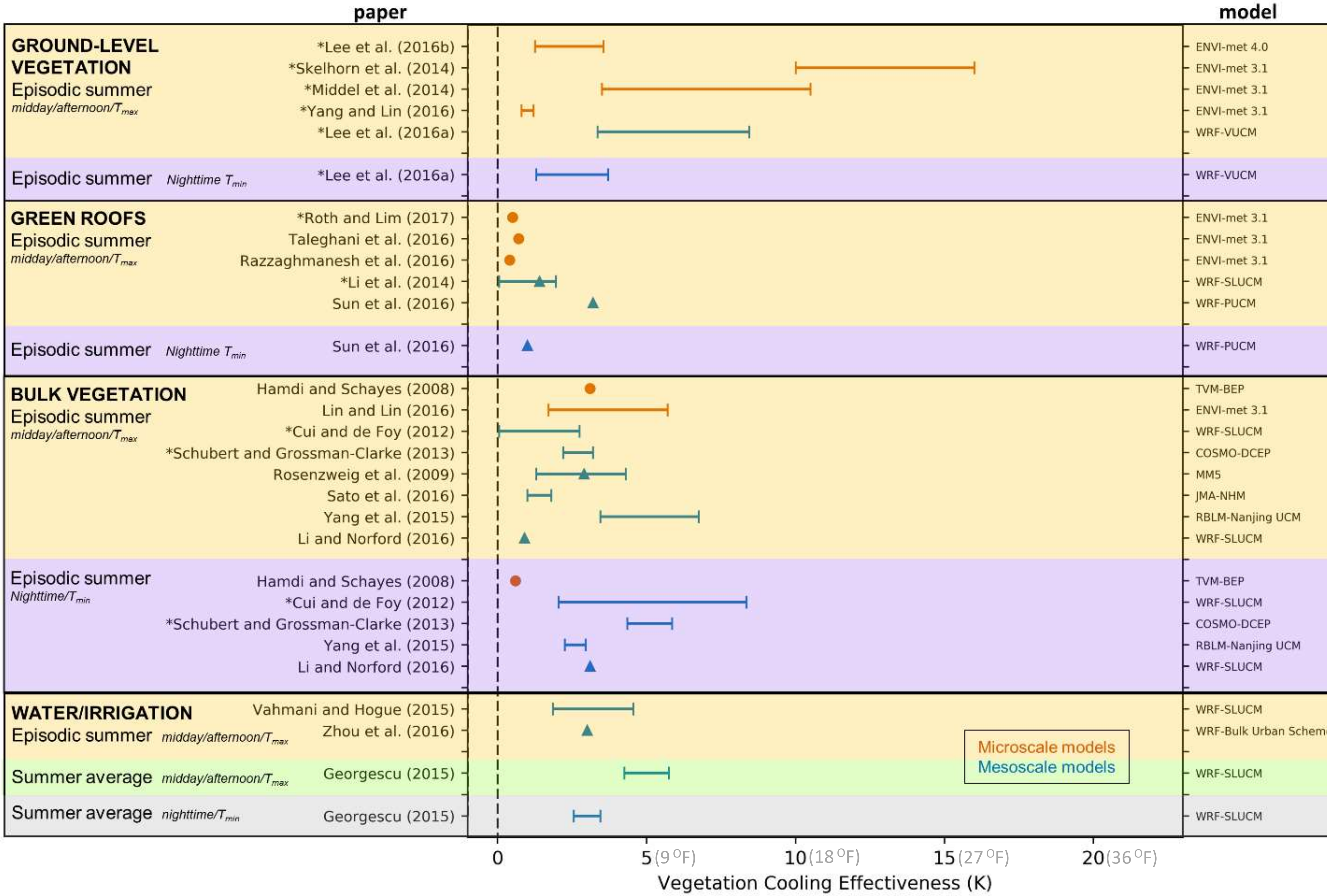


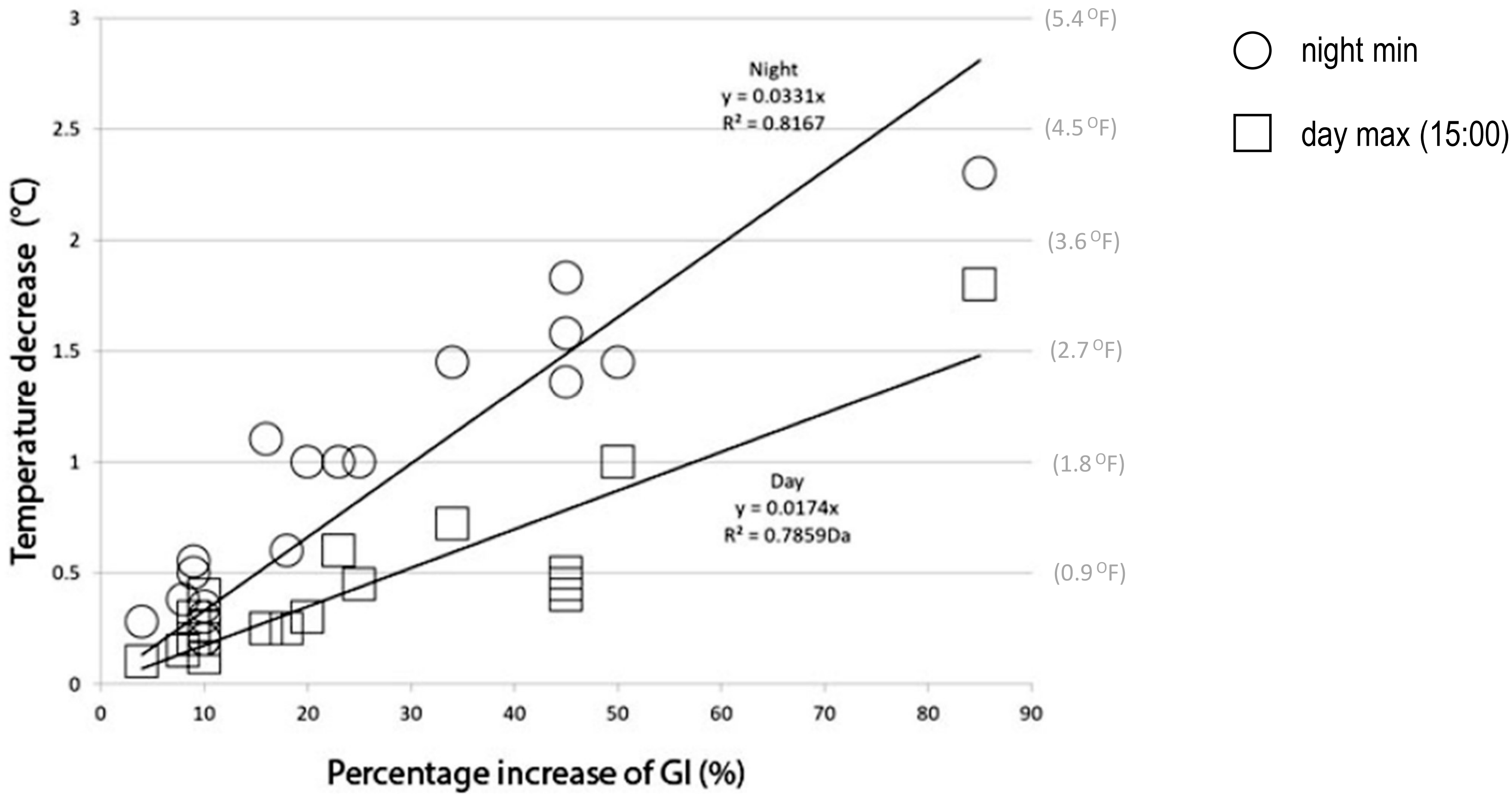
Figure 7: Vegetation cooling effectiveness (*VCE*) from street tree (a) and other (b) vegetation implementations for two model scales and across several seasons and approximate times of day. Symbols are as in Fig. 6. Vertical, orange dashed lines in (a) indicate median *ACE* for summer afternoon microscale study results.

Vegetation cooling effectiveness (ii) other vegetation



Effect on increasing Green Infrastructure (GI) on air temperature

(Santamouris and Osmond, 2020)



Daily peak and night-time temperature drop as a function of increase in GI

Limitations: (i) Not all models are equal…

(Krayenhoff et al, 2020)

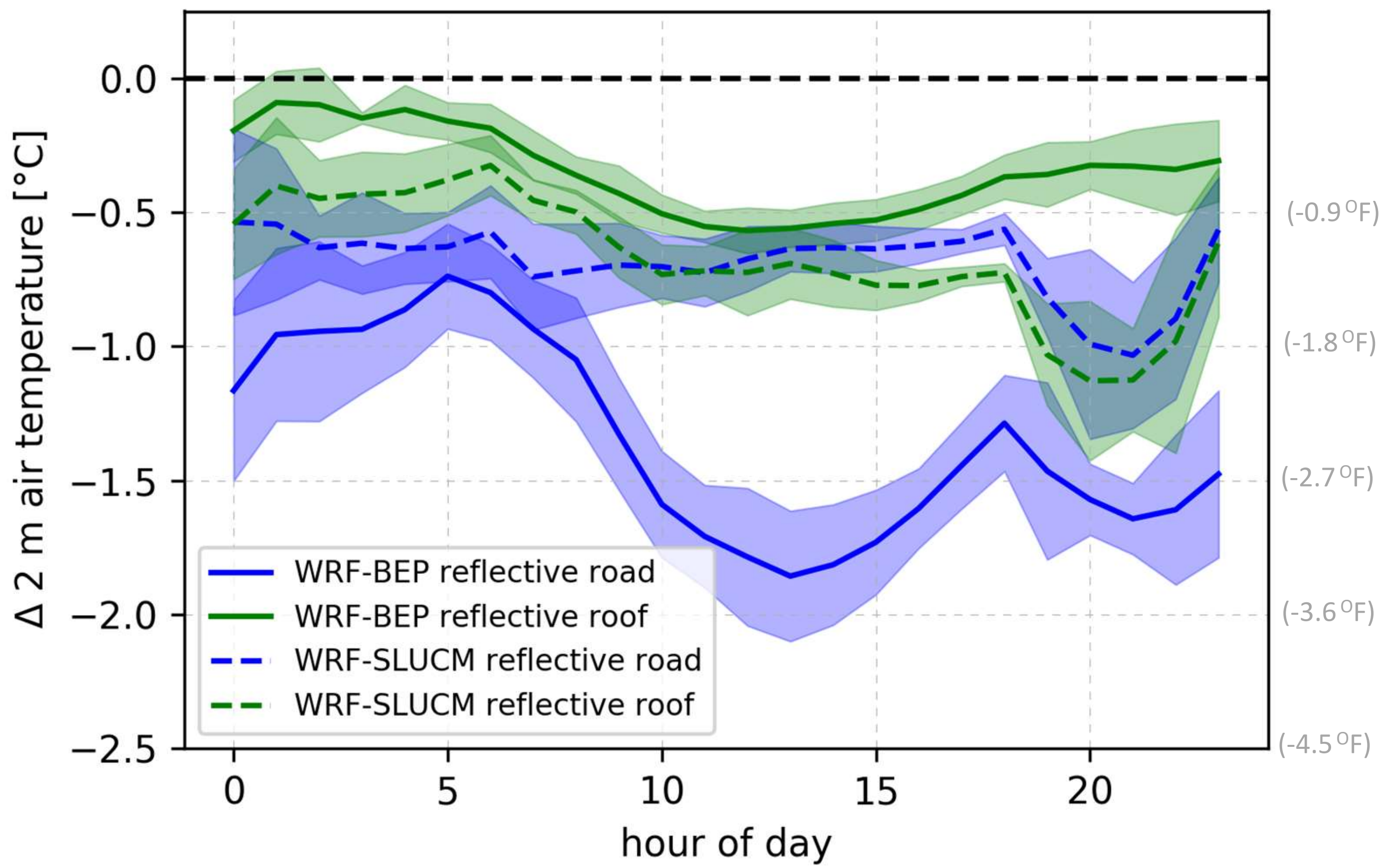
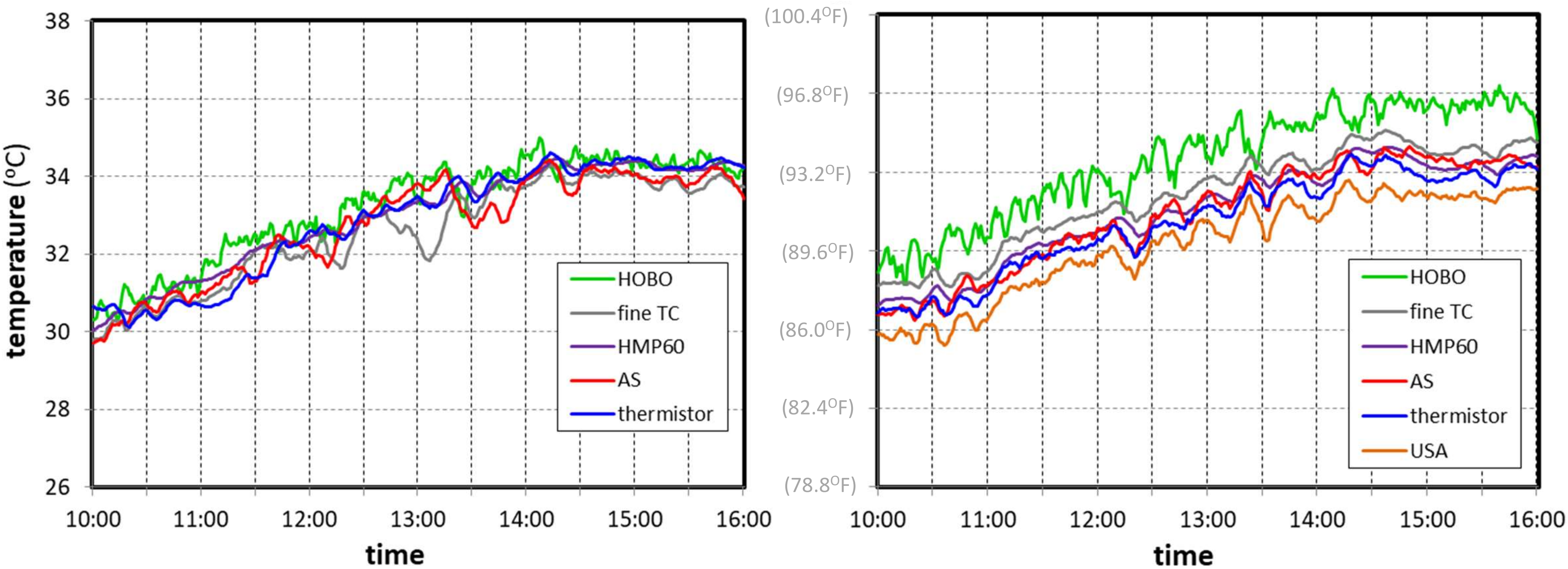


Figure 8: The importance of model physics representations of urban surface layer exchange on air temperature cooling from albedo enhancement. A diurnal composite of cooling during a 2006 heatwave in Phoenix studied by Broadbent et al. (2020a) is plotted for two urban canopy models (UCMs) embedded in the WRF mesoscale model. For each UCM, the albedo of road and roof are increased in separate simulations to 0.88.

Limitations: (ii) Measured data may be inaccurate, too

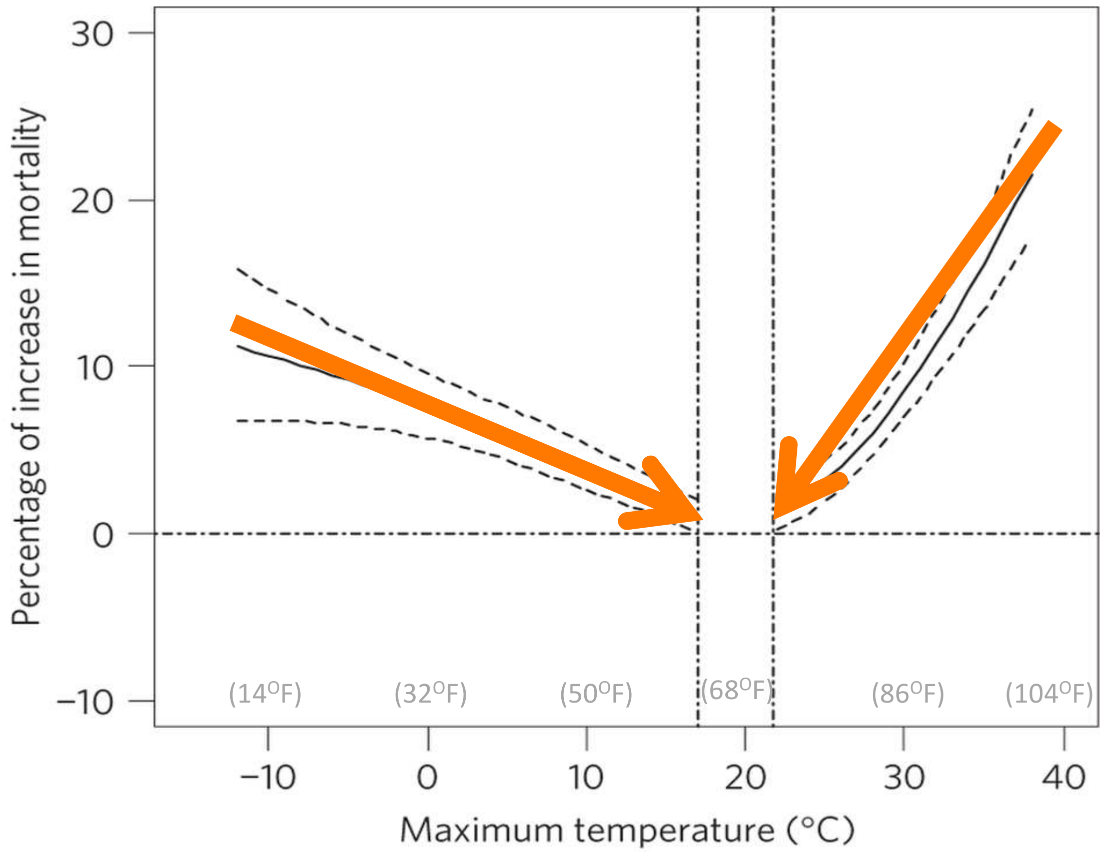
(Tzur and Erell, in preparation)



Dry bulb temperature of accurately calibrated scientific grade sensors in instrument screens. Left: beneath trees. Right: exposed to the sun

Human mortality increases when it's hot (and when it's cold)…

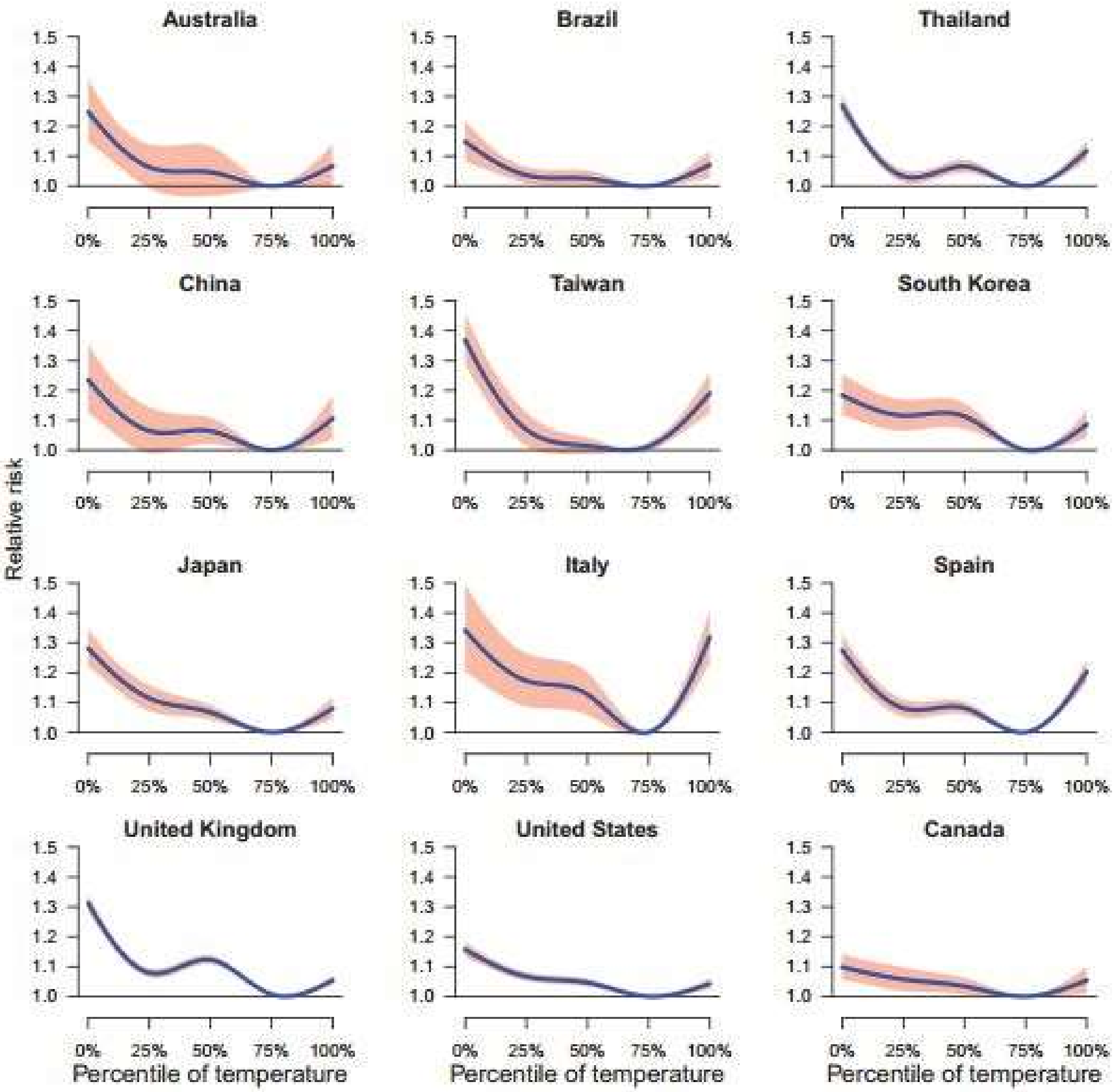
(Li et al, 2013)



Projections of seasonal patterns in temperature-related deaths for Manhattan

but heat–related mortality is mediated by country

(Guo et al, 2014)



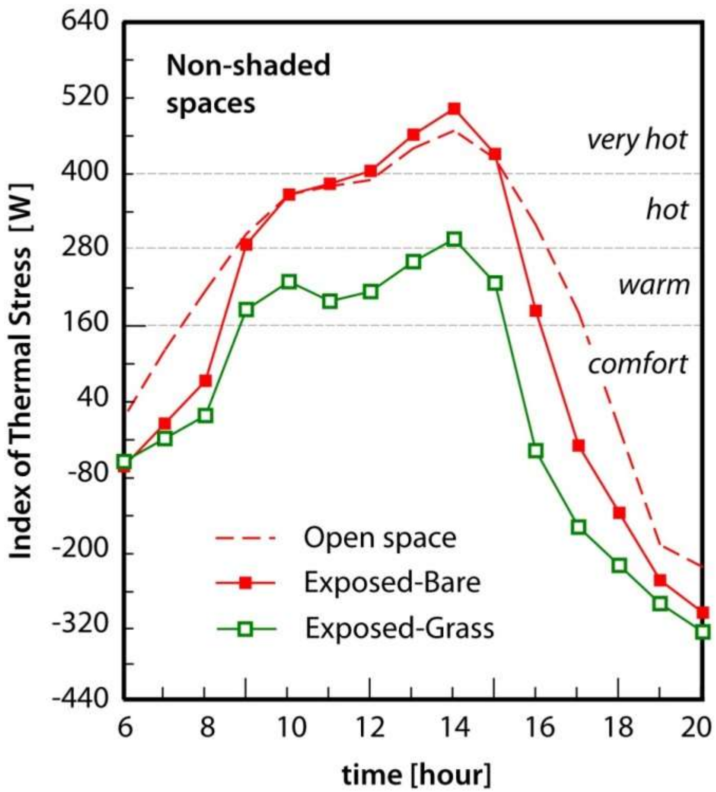
1st percentile is coldest, 99th percentile hottest

- The relative mortality risk for each country is at a minimum between the 66th and 80th percentile of mean temperature. Nine of the twelve countries have an “optimum” temperature between the 72nd and 76th percentiles.
- For each country, the relative mortality risk is substantially higher at the 1st percentile temperature (cold end) than at the 99th percentile (hot end).
- Remarkably, the above bullet points hold not only for relatively cold countries such as Canada and South Korea but also the relatively warm ones such as Brazil and Thailand.

Vegetation and thermal stress (i)

(Shashua-Bar et al, 2011)

"it's the cool surface and reduced IR flux…"



Index of Thermal Stress (ITS) is the equivalent latent heat of sweat evaporation required for the body to maintain thermal equilibrium under warm environmental conditions.

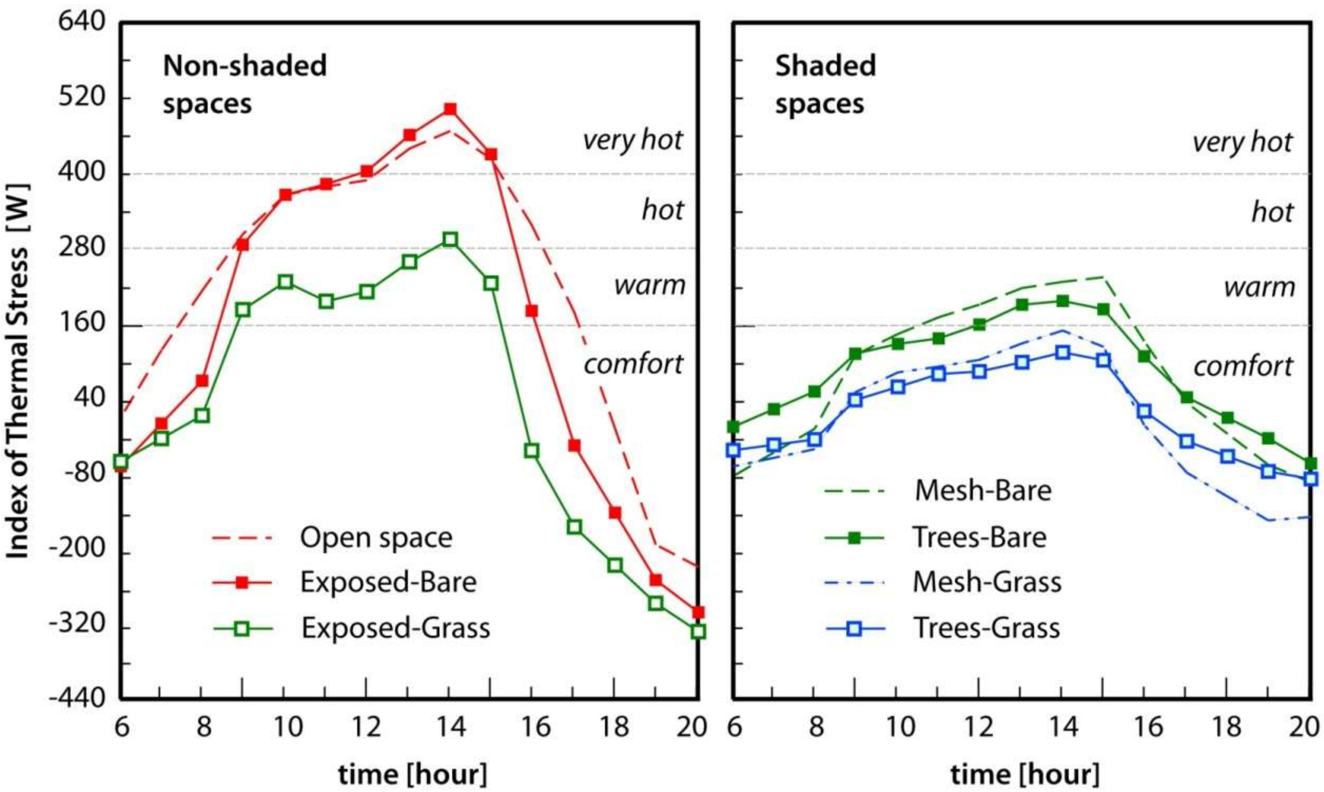
(Givoni, 1963; Pearlmutter et al, 2007)

Grass did NOT cool the air, but still reduced thermal stress

Vegetation and thermal stress (ii)

(Shashua-Bar et al, 2011)

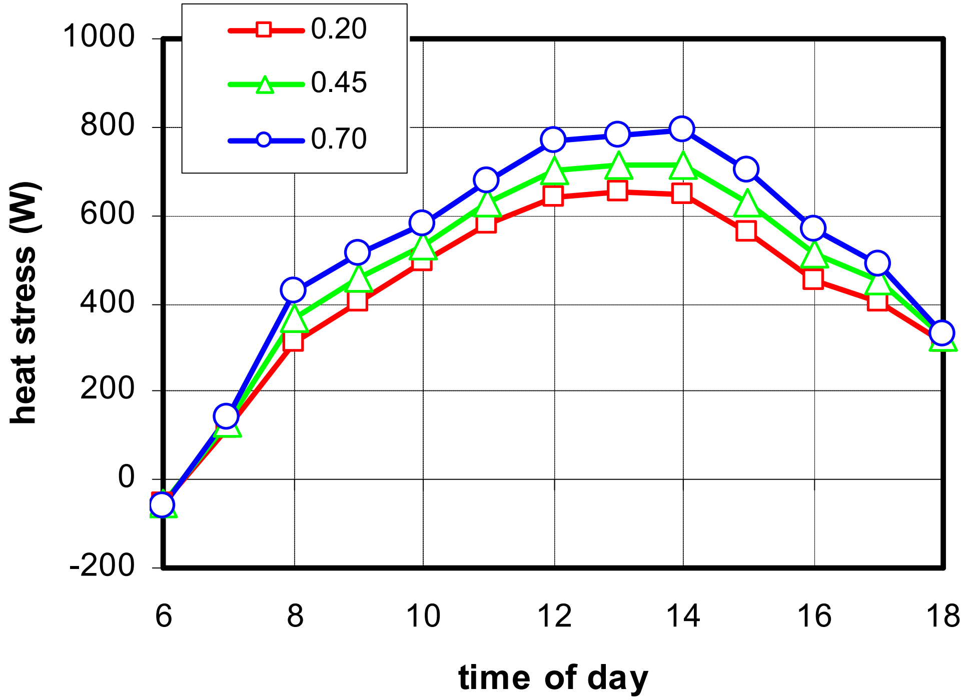
“it’s the shade…”

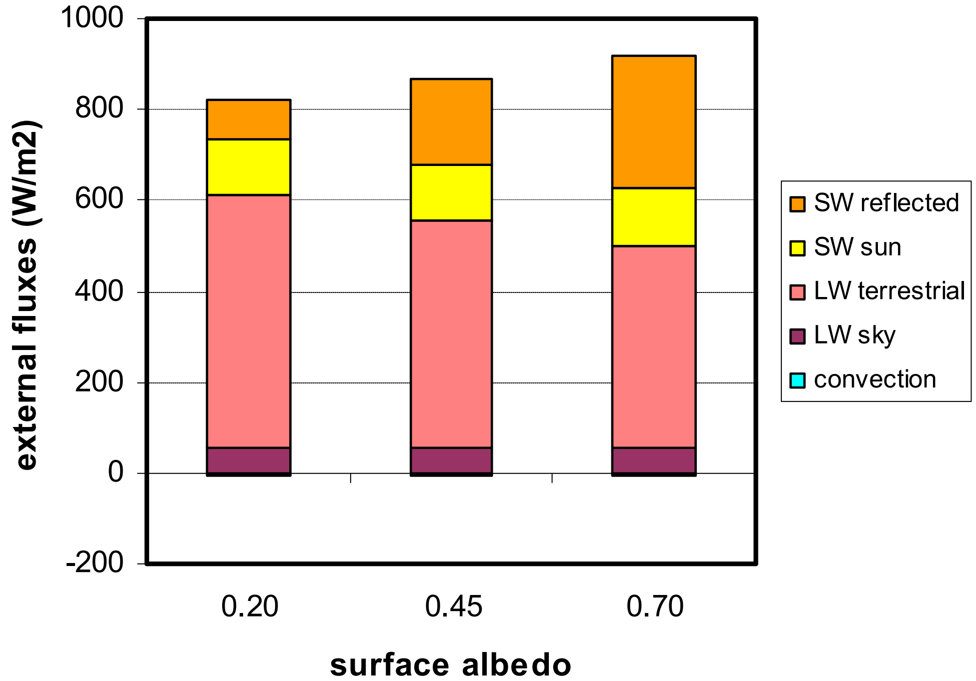


Trees and fabric shade had almost identical effect on thermal stress

Albedo and thermal stress (iv)

(Erell et al, 2014)





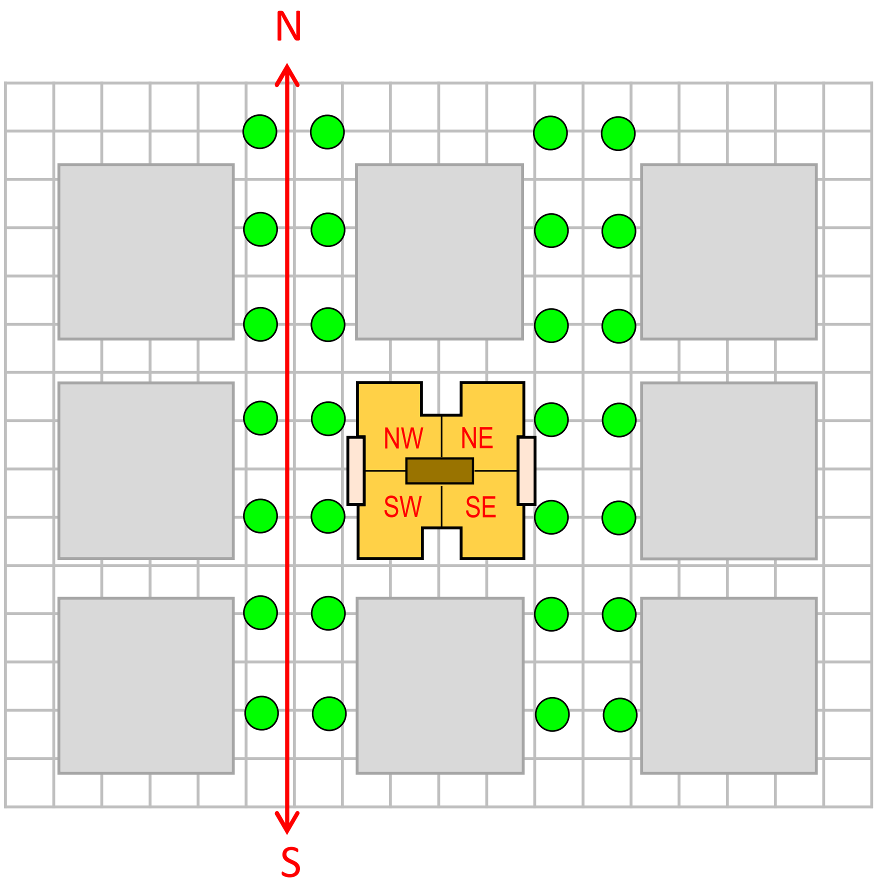
Canyon environment in Adelaide simulated by CAT on hot summer day used as input for calculating ITS for surfaces with different albedos (0.20, 0.45, 0.70)

* External (incoming) fluxes do not include LW radiation given off by the person or latent heat loss by sweat.

Increased solar reflection offsets effect of high albedo on surface temperature and IR emission: air temperature is lower but thermal stress on pedestrians is greater

EnergyPlus simulation – building energy consumption

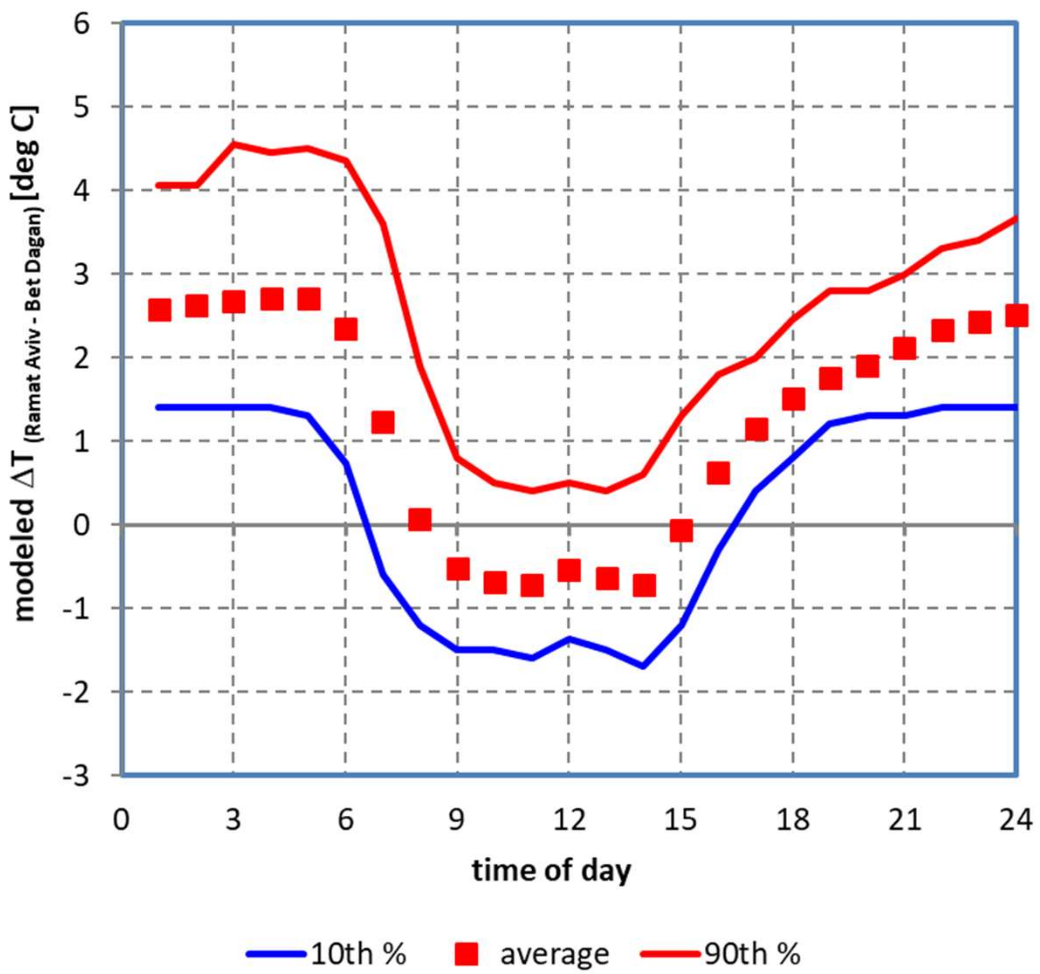
(Erell and Zhou, submitted)



- EnergyPlus building thermal simulation (using ENERGYui interface developed for Israel standard)
- Occupancy, internal loads and HVAC set- points are fixed (20°C/68°F winter, 24°C/75.2°F summer)
- Shading by adjacent buildings of equal height modeled by adding non-conditioned extensions to the building
- Add vegetation, then generate new 'urbanized' .epw input with CAT model, repeat…
- To isolate effect of vegetation, building dimensions, design features and material properties are unchanged

Simulated temperature anomaly (Ramat Aviv hot spot)

(Erell and Zhou, submitted)



Annual distribution of simulated
ΔT (Ramat Aviv – Bet Dagan)

- Large diurnal variance
- UHI is mostly nocturnal
- But some nights have only modest UHI
- Daytime UHI negligible

Modelled energy demand for HVAC ('standard' 8 story building, Tel Aviv)

(Erell and Zhou, submitted)

	electricity consumption (kWh)		
	heating	**cooling**	**total HVAC**
Bet Dagan (ref weather stn)	20,053	34,636	54,689
Ramat Aviv (urban hot spot)	10,587	40,503	51,090
diff (kWh)	-9,466	5,867	-3,599
diff (%)	-52.8	16.9	-6.6
Ramat Aviv with 50% plant cover	11,681	38,048	49,729
diff (kWh)	1,094	-2,455	-1,361
diff (%)	10.3	-6.1	-2.7

In this case (!), the UHI effect reduces heating more than it increases cooling.

Take home message

Urban heat varies substantially in space cities are very heterogenous) and time (heat islands are mostly nocturnal)

Air temperature is a good 'headline' indicator of weather conditions – but when used as the primary tool for assessing the impact of proposed interventions, it might lead to inaccurate or even erroneous conclusions.

More useful benefits of heat mitigation studies may include recommendations for strategies based on their contribution to practical benefits:

a. Improving human thermal comfort (esp. in outdoor spaces) – **response to impact of climate change**

b. Conserving energy in buildings – **to reduce GHG emissions and combat climate change**

Detailed, site-specific simulation should include effects of all aspects of climate modification – shading, air temperature, humidity, wind speed etc.

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Questions?

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