Environmental impacts of reflective materials: Is high albedo a 'silver bullet' for mitigating urban heat island?

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June 18, 2015

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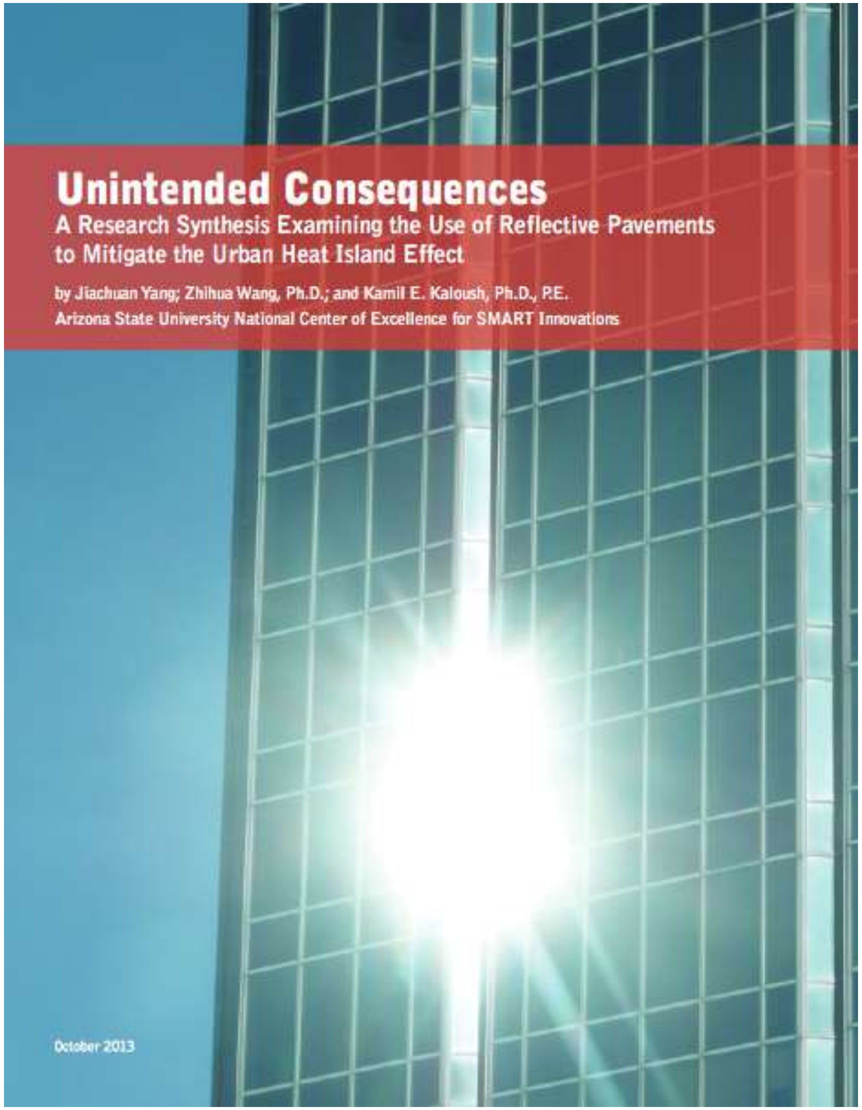
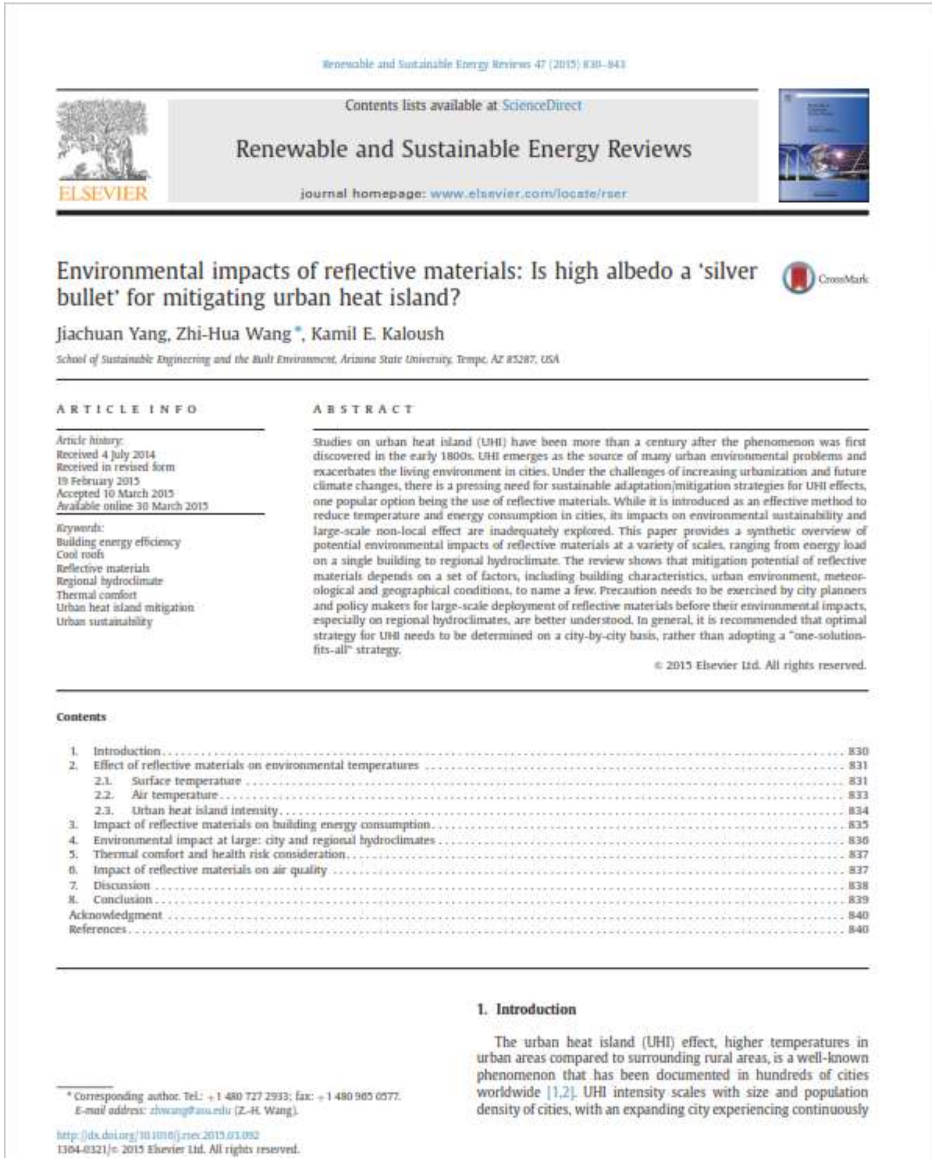


- Focus on unintended consequence
- Review about 60 references
- Deployment of reflective pavement to mitigate UHI requires further detailed investigation
- Create a healthy debate



Renewable and Sustainable Energy Reviews 47 (2015) 830–843

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Environmental impacts of reflective materials: Is high albedo a 'silver bullet' for mitigating urban heat island?

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ARTICLE INFO

Article history:
Received 4 July 2014
Received in revised form
19 February 2015
Accepted 10 March 2015
Available online 30 March 2015

Keywords:
Building energy efficiency
Cool roofs
Reflective materials
Regional hydroclimate
Thermal comfort
Urban heat island mitigation
Urban sustainability

ABSTRACT

Studies on urban heat island (UHI) have been more than a century after the phenomenon was first discovered in the early 1800s. UHI emerges as the source of many urban environmental problems and exacerbates the living environment in cities. Under the challenges of increasing urbanization and future climate changes, there is a pressing need for sustainable adaptation/mitigation strategies for UHI effects, one popular option being the use of reflective materials. While it is introduced as an effective method to reduce temperature and energy consumption in cities, its impacts on environmental sustainability and large-scale non-local effect are inadequately explored. This paper provides a synthetic overview of potential environmental impacts of reflective materials at a variety of scales, ranging from energy load on a single building to regional hydroclimate. The review shows that mitigation potential of reflective materials depends on a set of factors, including building characteristics, urban environment, meteorological and geographical conditions, to name a few. Precaution needs to be exercised by city planners and policy makers for large-scale deployment of reflective materials before their environmental impacts, especially on regional hydroclimates, are better understood. In general, it is recommended that optimal strategy for UHI needs to be determined on a city-by-city basis, rather than adopting a "one-solution-fits-all" strategy.

Contents

1. Introduction

The urban heat island (UHI) effect, higher temperatures in urban areas compared to surrounding rural areas, is a well-known phenomenon that has been documented in hundreds of cities worldwide [1,2]. UHI intensity scales with size and population density of cities, with an expanding city experiencing continuously

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http://dx.doi.org/10.1016/j.rser.2015.03.092
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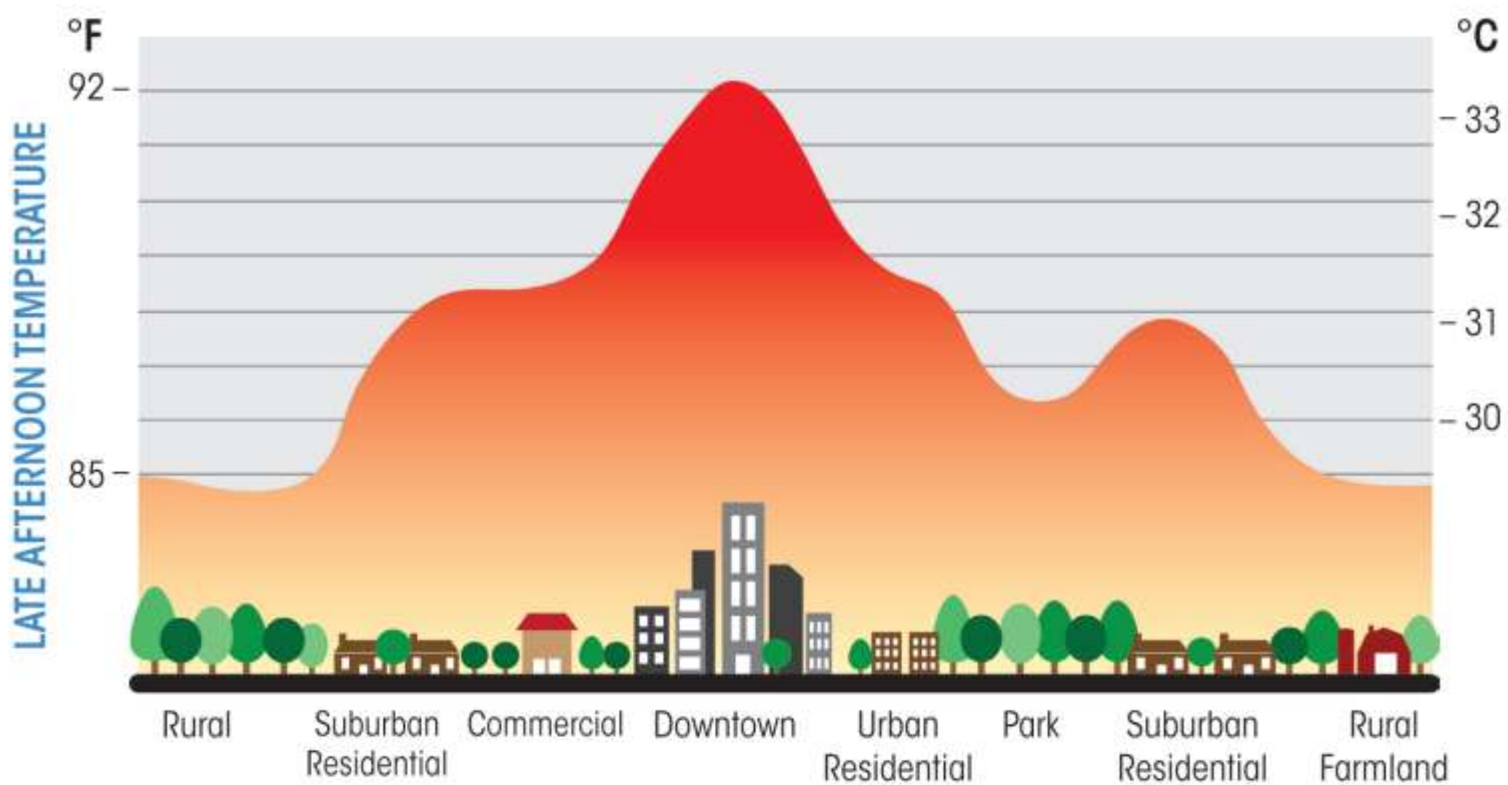
- Aims to provide a more comprehensive study
- Review about 179 references
- Optimal mitigation strategy for UHI needs to be determined on a city-by-city basis, rather than a "one-solution-fit-all" strategy

- Introduction: Urban heat island
- Effect of reflective material
- Discussion: Important factors
- Concluding remark

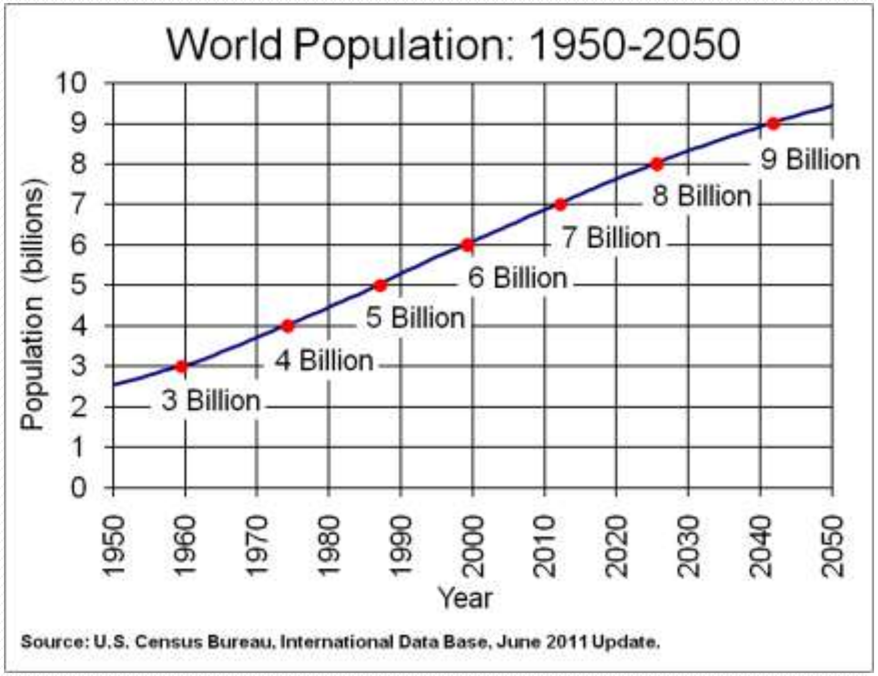
What is Urban Heat Island?

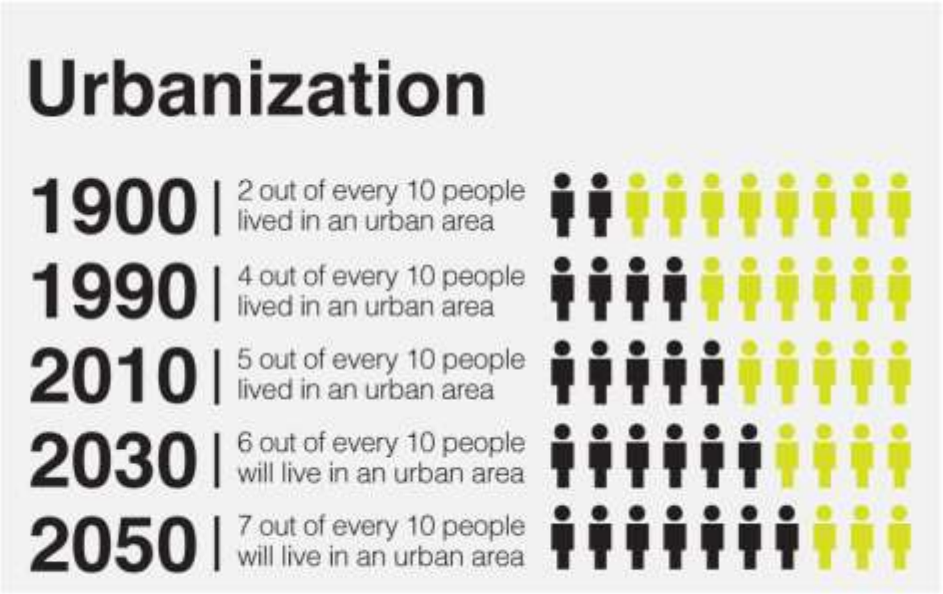
Higher temperature in urban areas as compared to rural surroundings



Source: Heat island group, LBNL

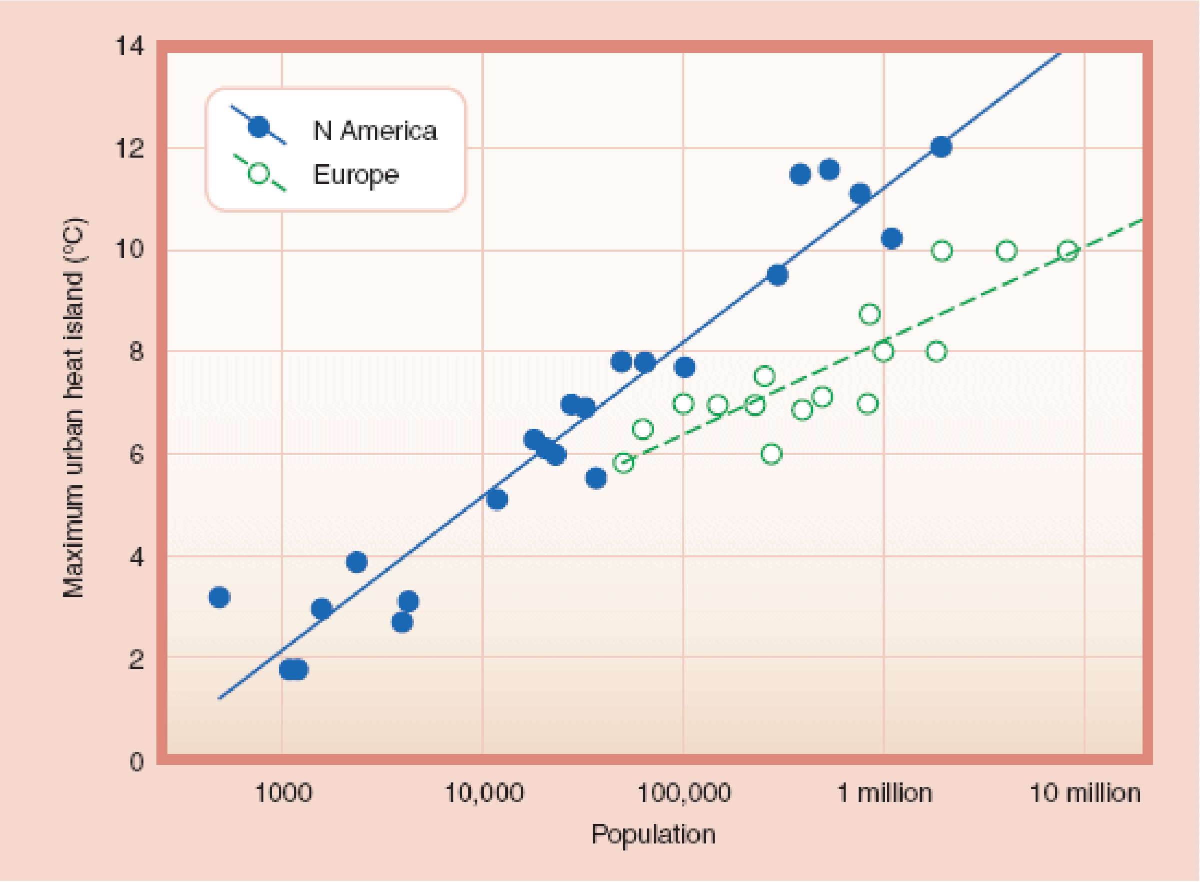
Increasingly urbanized population





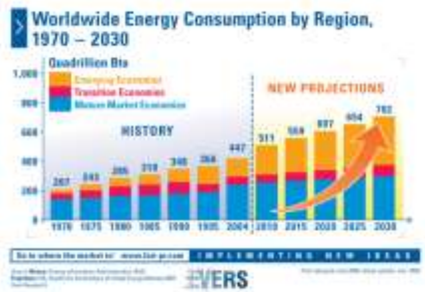
Defined by UN HABITAT as a city with a population of more than 10 million

Urban heat island intensity

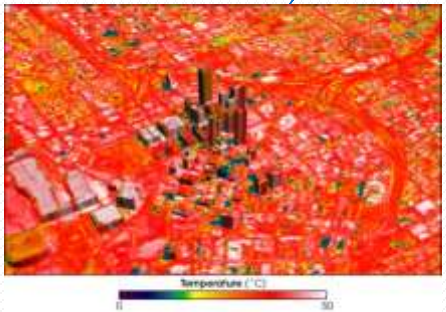


Source: CIMSS, University of Wisconsin-Madison

Adverse effects of UHI



Increased energy consumption



High temperature

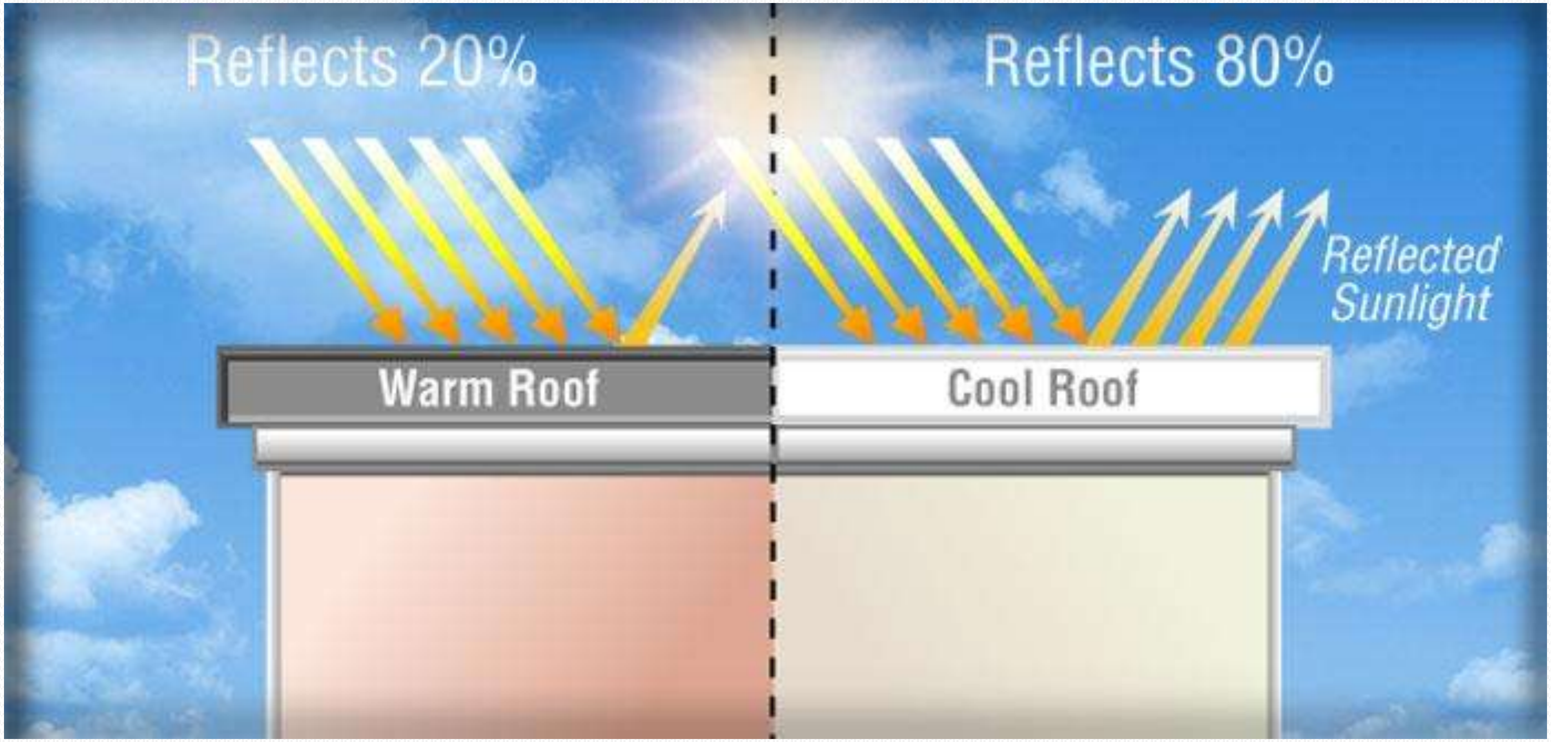
Air pollution

Extreme rainfall

Thermal stress

Reflective material

Reflectivity: the ratio of reflected radiation from the surface to incident radiation upon it



Source: Heat island group, LBNL

Scope of the study

1. The literature published since 1990
2. Focus on major environmental impacts of reflective materials
3. Studies that were exclusively conducted on reflective materials
4. Include both reflective roof and reflective pavement
5. In total 179 references were reviewed

Effect of reflective material

1. Temperature (surface / air)
2. Building energy consumption
3. Regional hydroclimate
4. Thermal comfort and health risk
5. Air quality

Effect of reflective material on surface temperature

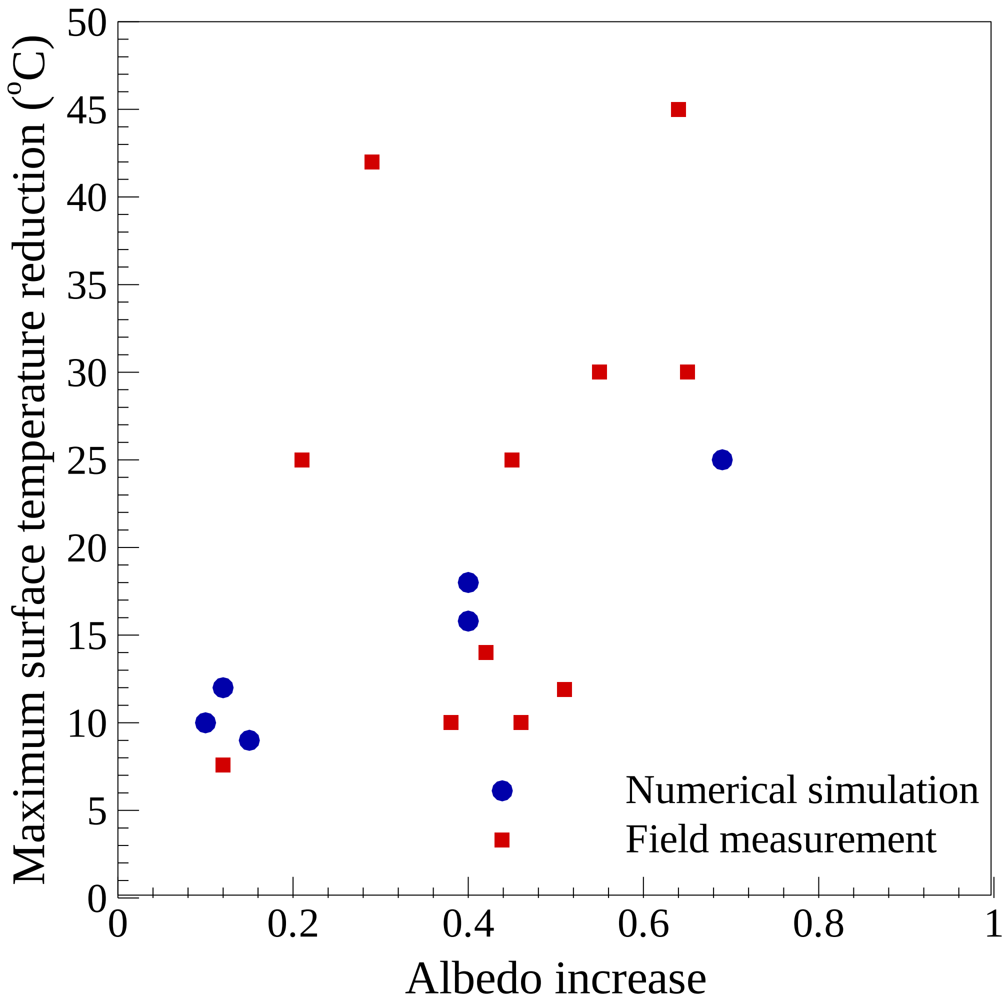
Pros:

- Absorb less radiation and maintain a low daytime surface temperature

Cons:

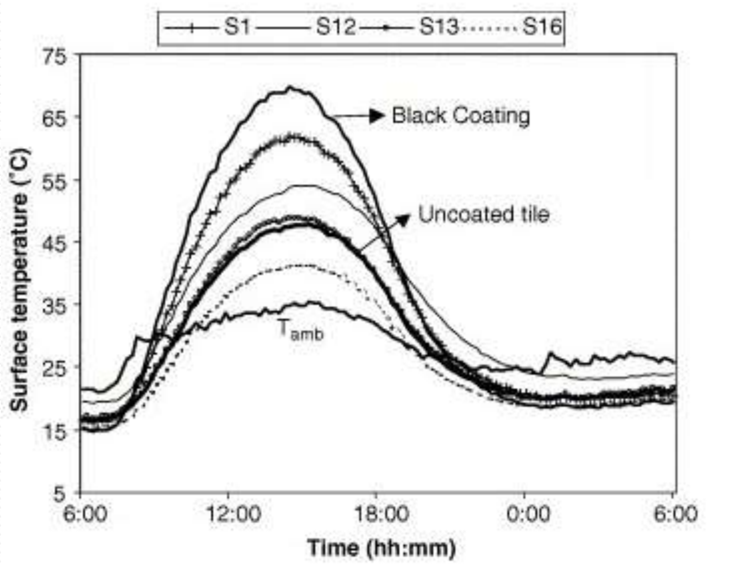
- Relatively ineffective during nighttime due to the absence of solar radiation (other thermal properties dominate)
- Reflected radiation from pavement can be absorbed by surrounding surfaces and subsequently increases their temperatures
- Effect on roofs depends on the urban geometry

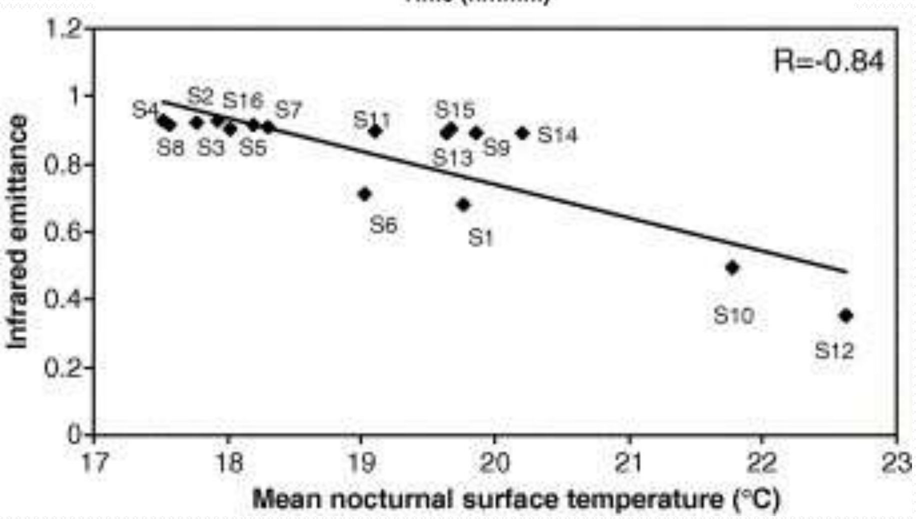
Surface cooling by reflective roofs



- Maximum daytime cooling up to about 45°C
- Significant cooling > 8°C in all studies

Effect of reflective material at nighttime

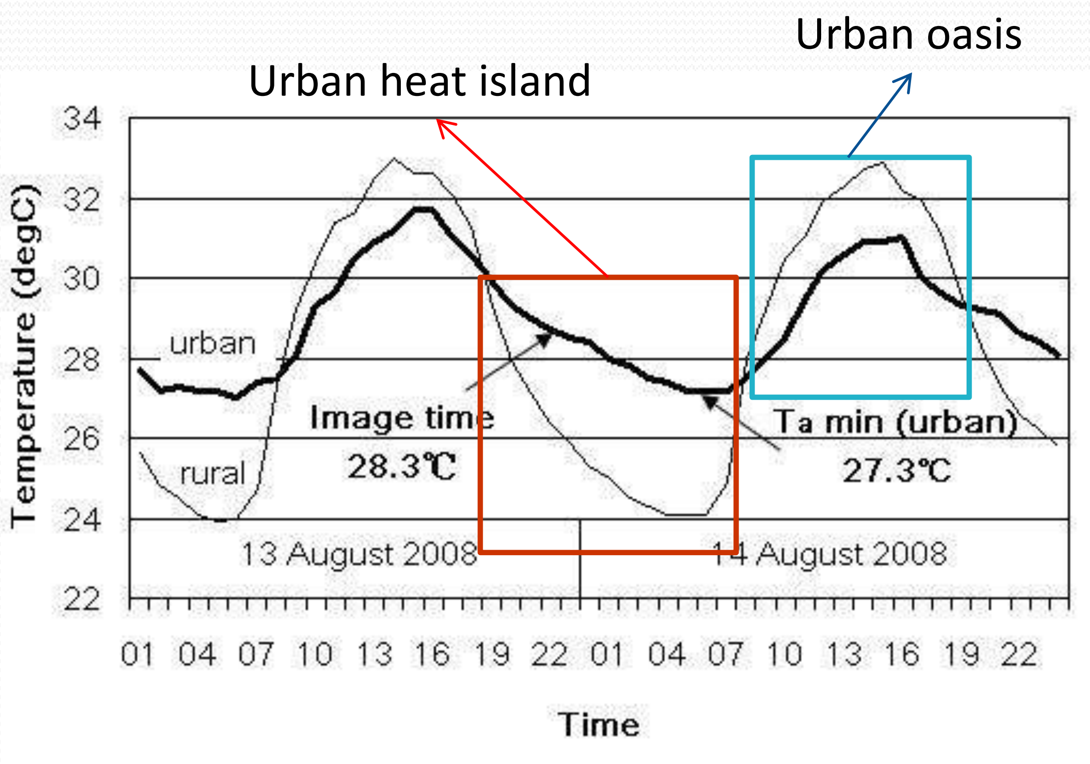




Synnefa et al. 2006. Solar Energy

- Field measurement of 18 different-coated white concrete pavement tiles (40 cm x 40 cm)
- Monitoring at a 24-h basis from August to October 2004
- Emissivity determines the nocturnal surface temperature of pavements

Diurnal UHI intensity



Nichol and To. 2011. Hong Kong Polytechnic University

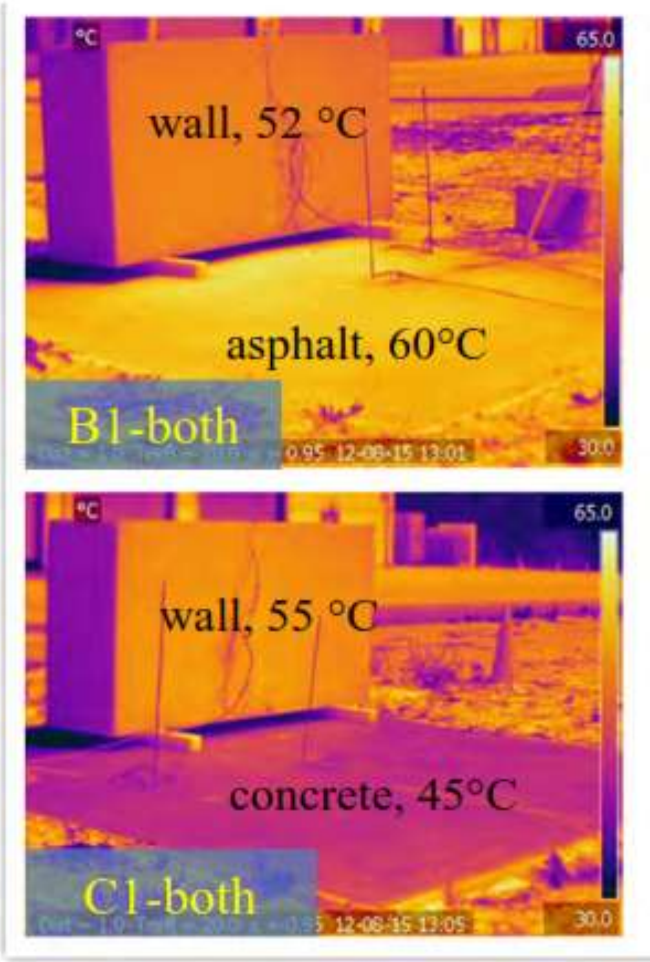
- Nighttime UHI intensity is more larger than daytime UHI intensity
- Reflective material may not be a effective strategy in terms of nighttime UHI mitigation

Heating of surroundings by reflected radiation

Hui Li. 2012. University of California, Davis

- Two walls (1.2 m x 2.4 m) made of same material, with a albedo of 0.29
- 4 m by 4 m asphalt (0.08) and concrete (0.28) pavements on ground
- Monitoring period: 2012 summer

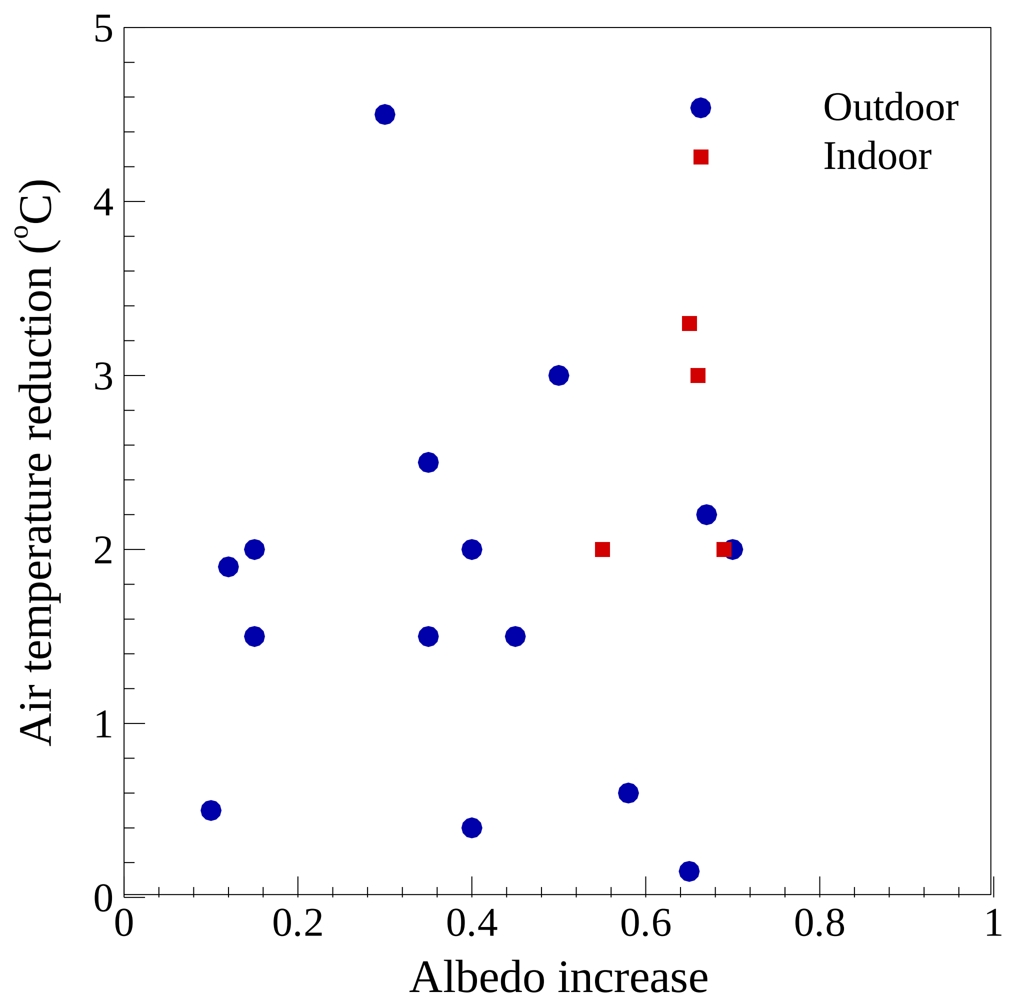
Heating of surroundings by reflected radiation



Hui Li. 2012. University of California, Davis

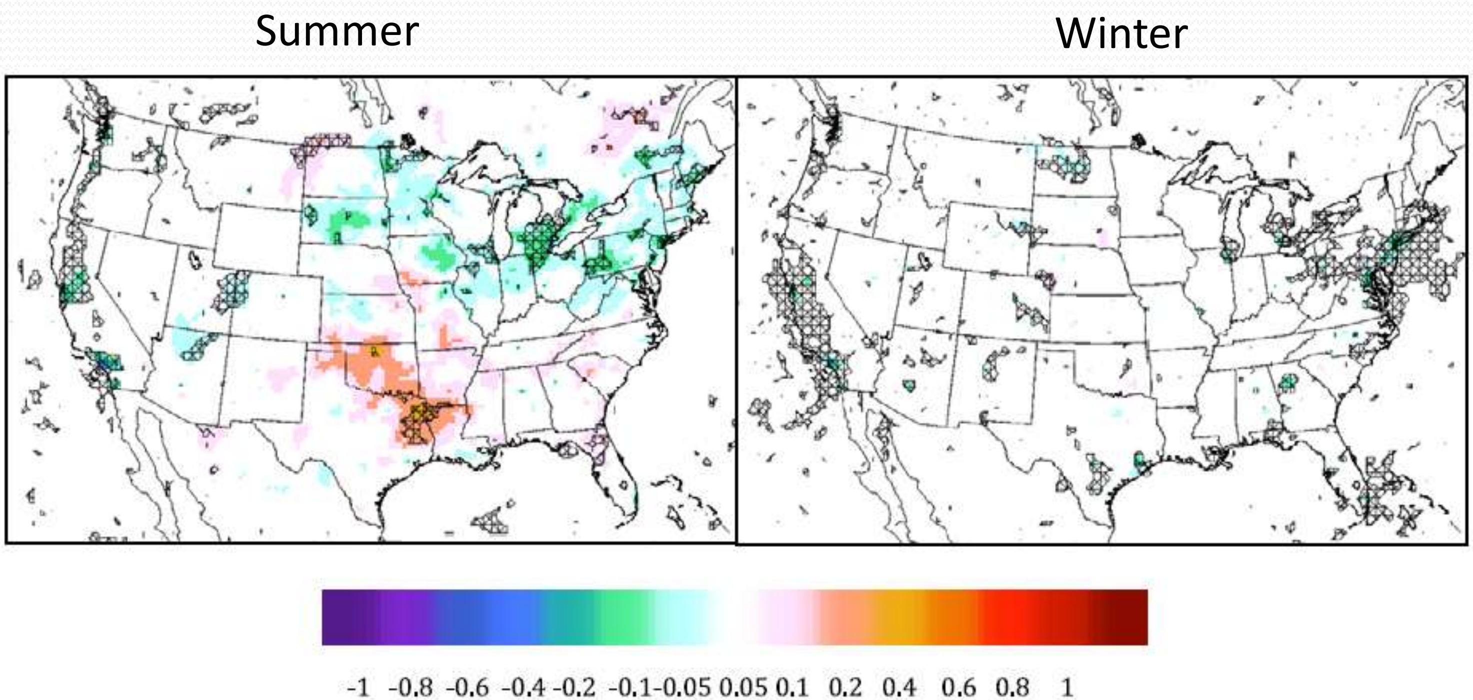
- Lower temperature on concrete pavement, with a higher wall temperature
- Special attention should be given to thermal interaction
- The effect tends to be more significant for high-density urban area

Cooling of air by reflective roofs



- Significant cooling for non-air-conditioned indoor environment (> 2°C)
- Great variability for outdoor effects: 0.1 – 4.6 °C depends on experimental setup

Effect of reflective material on regional air temperature



Millstein and Menon. 2011. Environ. Res. Lett.

- Albedo increase: 0.25 for roof and 0.15 for pavement
- Cooling up to 0.53 °C in cities at 1 pm PST during summer
- Unintended consequence: heating up to 0.27 °C in rural area

Effect of reflective material on building energy consumption

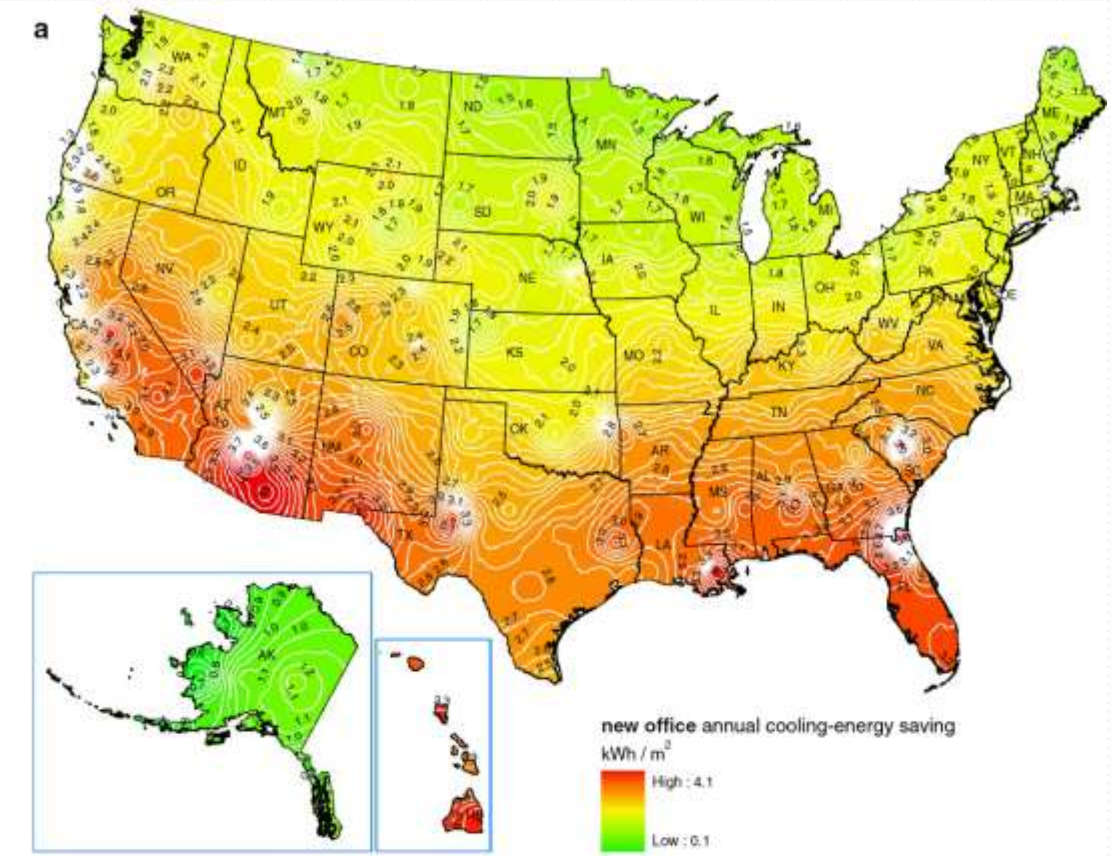
Pros:

- Reduce cooling loads of buildings during hot periods

Cons:

- Increase heating loads during cold seasons
- Increased cooling loads of adjacent buildings by reflected solar radiation from reflective surfaces (mostly applicable to pavement)

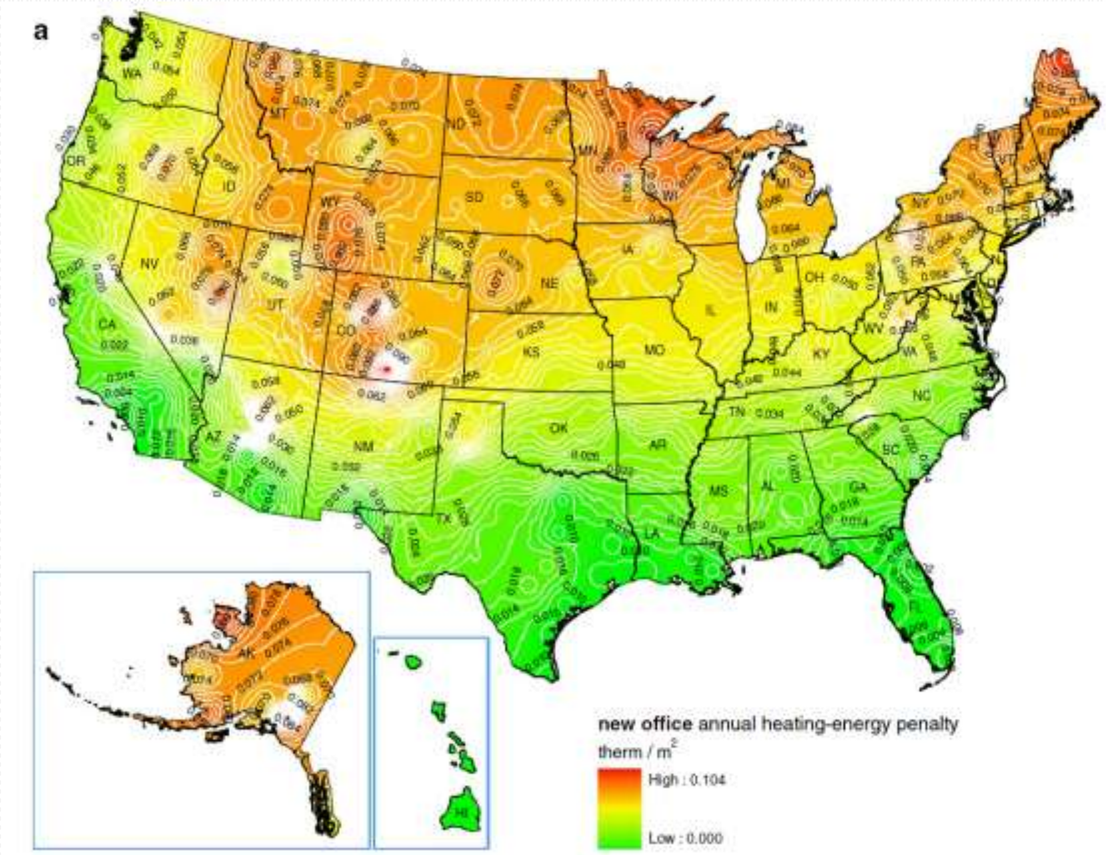
Effect of reflective material on cooling saving



Levinson and Akbari. 2009. Energy Effic.

- Roof albedo increased from 0.2 to 0.55
- Combine building energy simulation, local energy prices, building density
- Saving up to 4.1 kWh/m^2

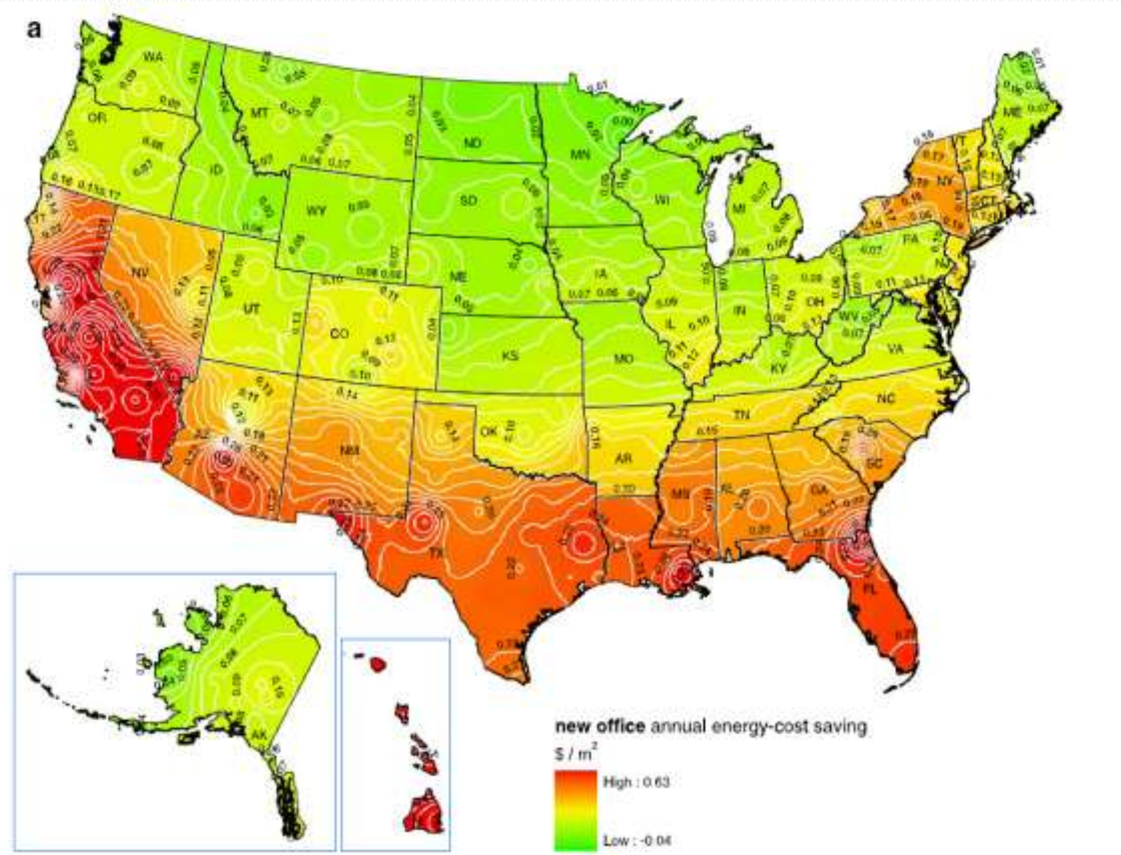
Effect of reflective material on heating penalty



Levinson and Akbari. 2009. Energy Effic.

- Heating penalty up to 0.104 therm/m^2

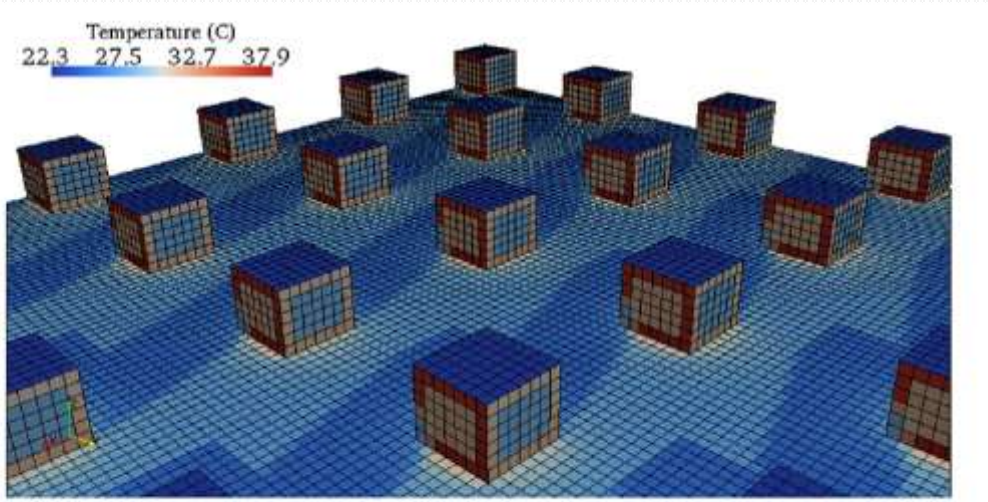
Effect of reflective material on net energy-cost saving



Levinson and Akbari. 2009. Energy Effic.

- Significant saving at the south, and slightly increased net energy-cost at the north
- Geographical and meteorological conditions play a crucial role

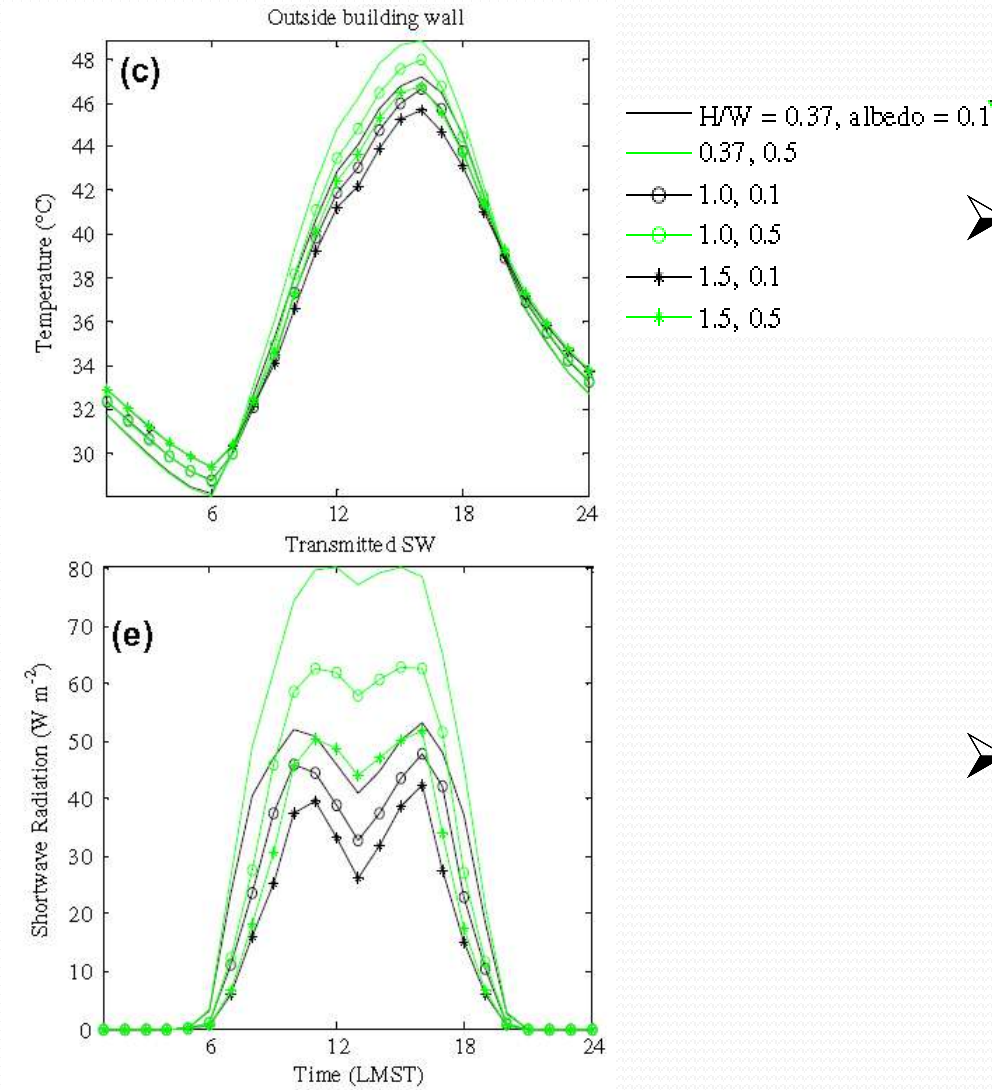
Effect of reflective material on adjacent buildings



Yaghoobian and Kleissl. 2012. Urban Clim.

- 3D numerical simulation (TUF-IOBES)
- 4-storey building at Phoenix assuming continuous HVAC operation
- Simulation period: July 15th

Effect of reflective material on adjacent buildings

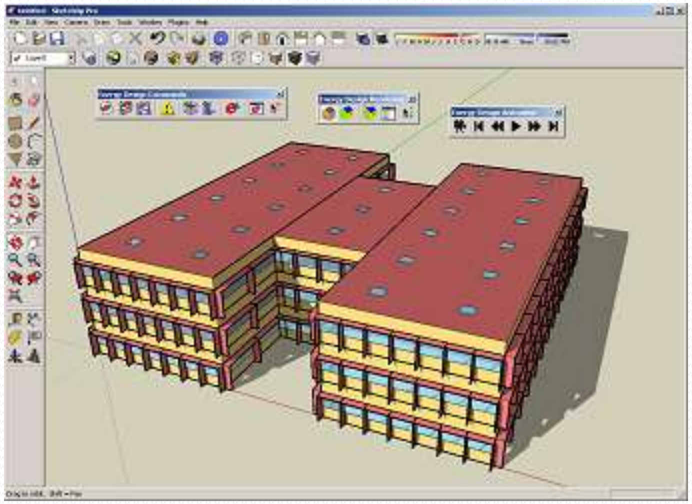


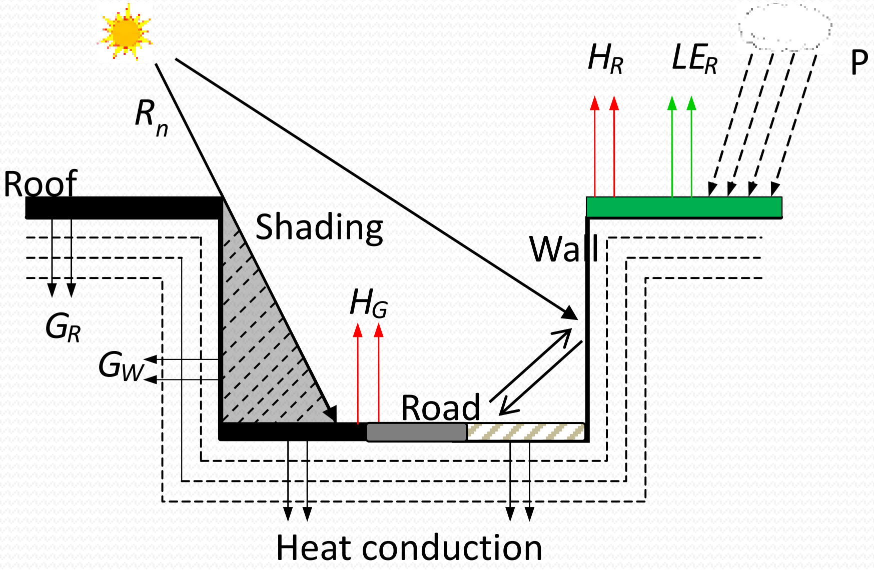
- Building wall temperature and shortwave radiation transmitted through window increase with pavement albedo
- Canyon aspect ratio affects thermal condition of buildings

Yaghoobian and Kleissl. 2012. Urban Clim.

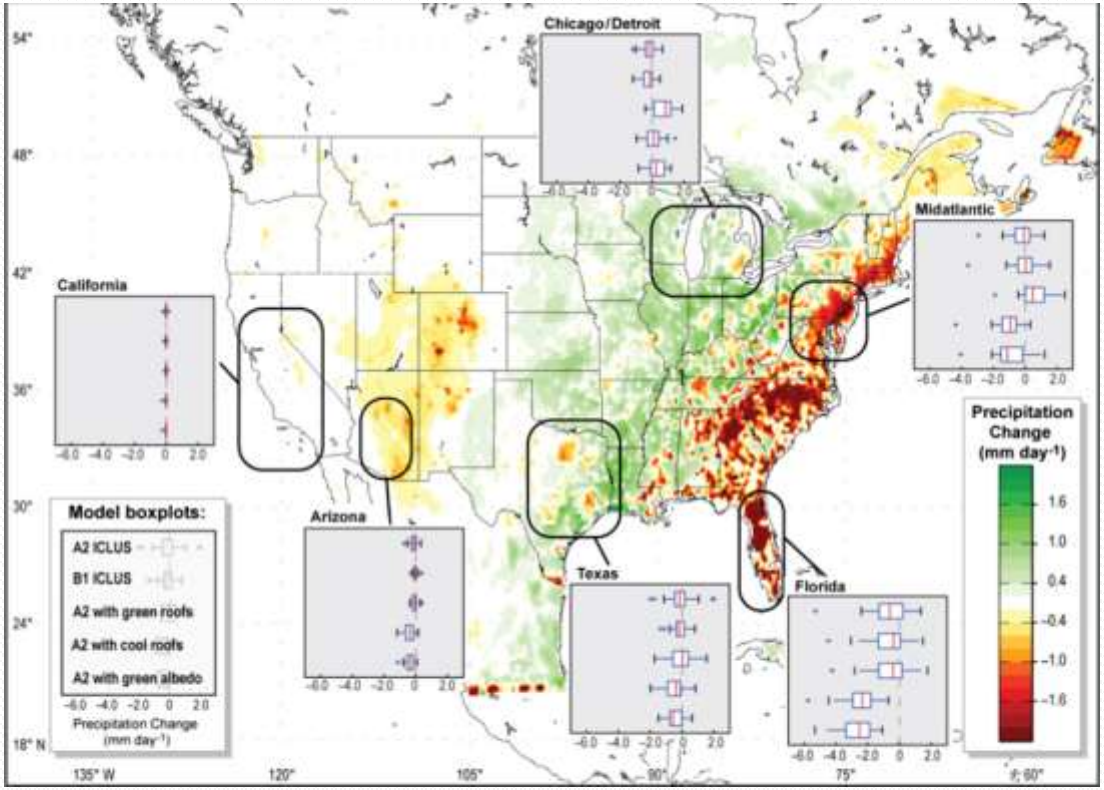
Discussion

- In-situ energy consumption data is mostly only available in summers
- Impact of urban geometry and thermal interaction is often neglected





Effect of reflective material on regional hydroclimate



Georgescu et al. 2014. Proc Natl Acad Sci USA

- Roof albedo increased to 0.88
- Significant reduction in summer precipitation at southeastern U.S.
- Limited amount of study on large scale impact of reflective material

Effect of reflective material on thermal comfort and health risk

Pros:

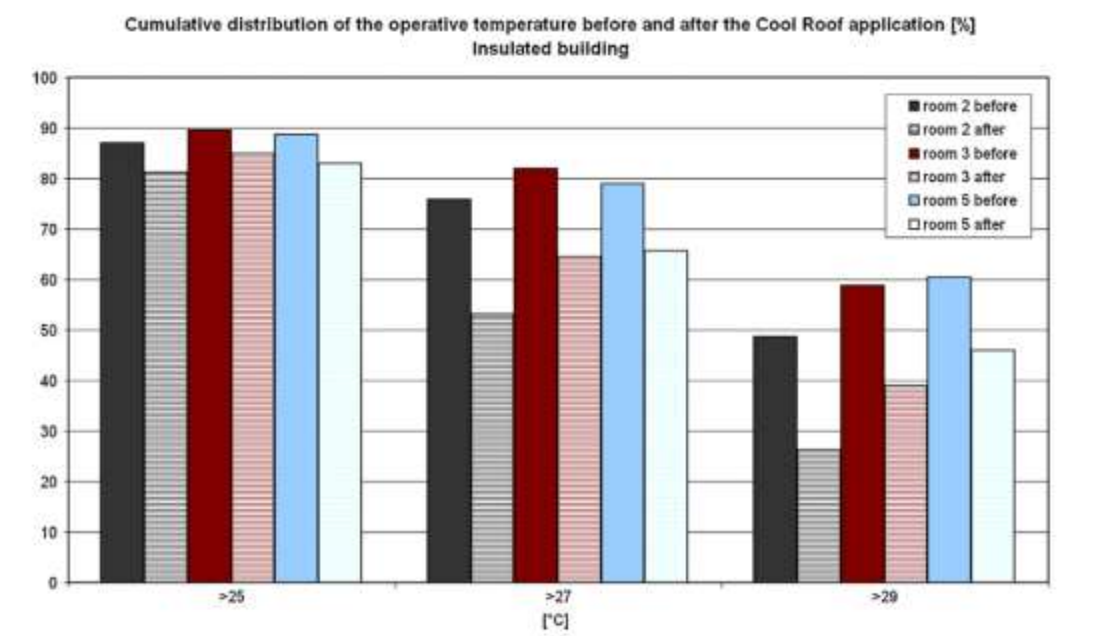
- Enhance non-air-conditioned indoor thermal comfort

Cons:

- Reflected UV radiation is harmful to living cells
- Upward reflected light cause light pollution

  (efforts to develop reflective materials that absorb in visible part of spectrum but exhibit high reflection in the near infrared part)

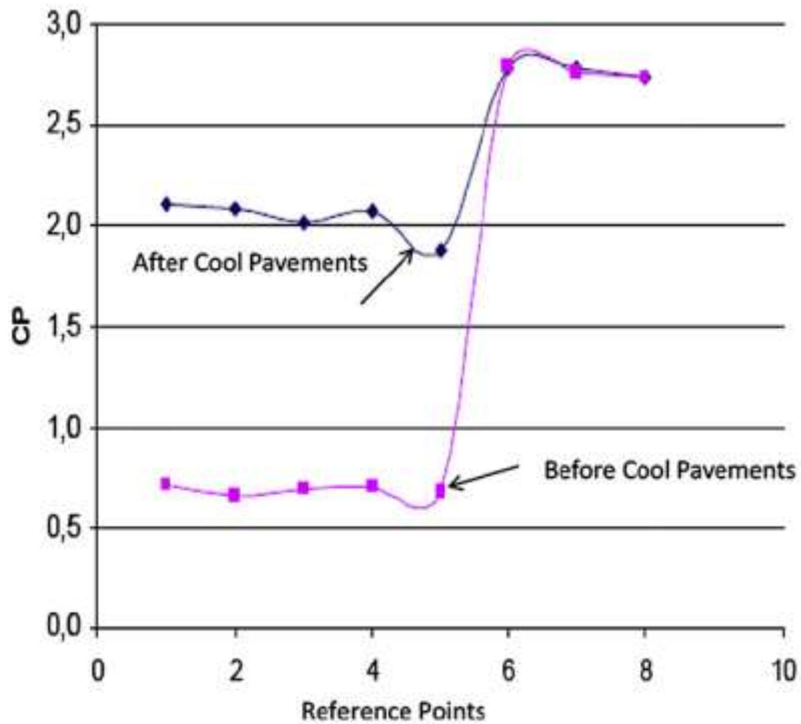
Effect of reflective material on indoor thermal comfort



Romeo and Zinzi. 2013. Energy Build.

- Non-air-conditioned school building in Trapani, Italy
- Roof albedo increased from 0.25 to 0.82
- Cool roof notably enhance indoor thermal comfort
- Benefits are more clear for higher thermal levels

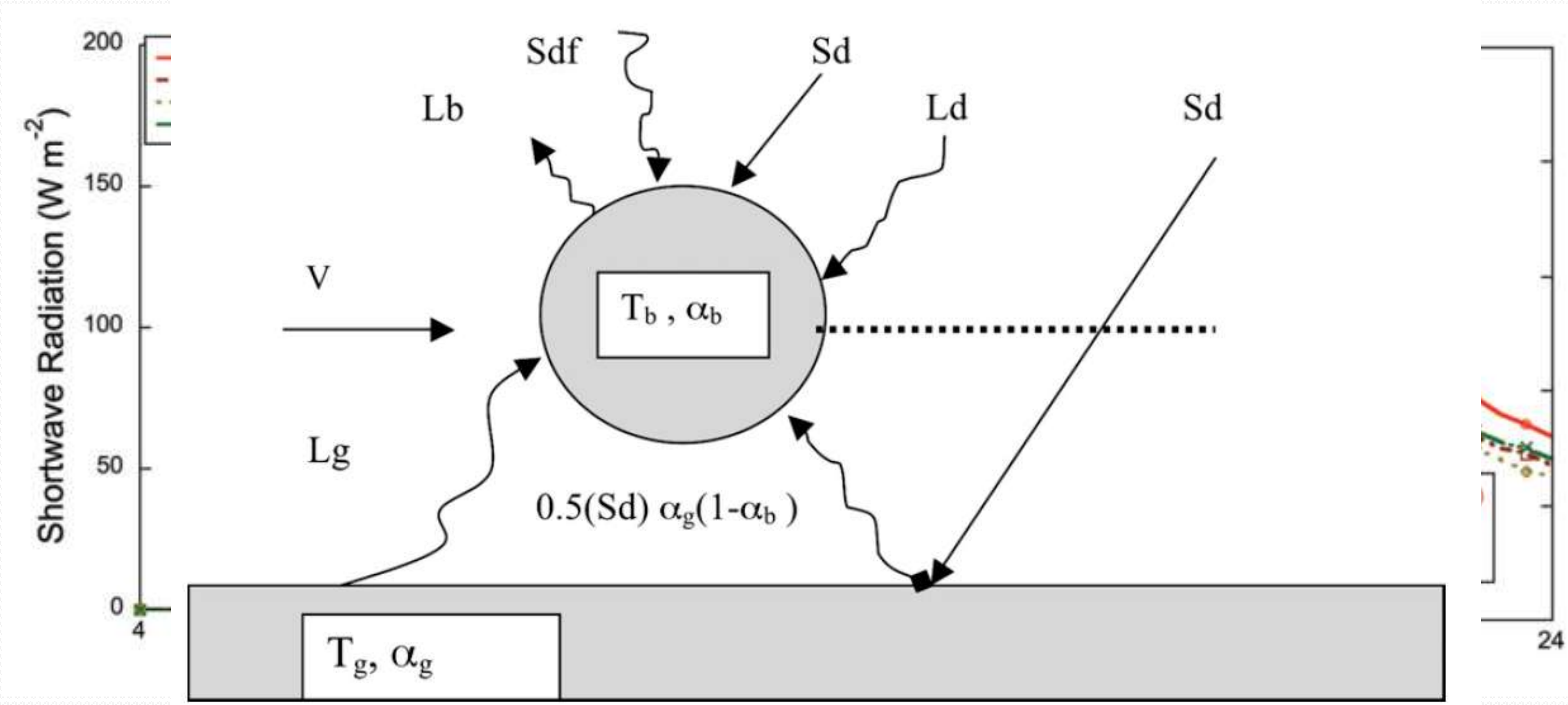
Effect of reflective material on outdoor thermal comfort



Santamouris et al. 2012. Build. Environ.

- Albedo increased from 0.48 to 0.6
- Cooling power comfort index: air temperature, wind speed
- Improvement is negligible at locations close to the sea

Effect of reflective material on outdoor thermal comfort



Lynn et al. 2009. J. Appl. Meteorol. Climatol.

- Increasing pavement albedo leads to increased shortwave and reduced longwave radiation towards pedestrians
- The net effect results in aggravated thermal stress

Effect of reflective material on Air quality

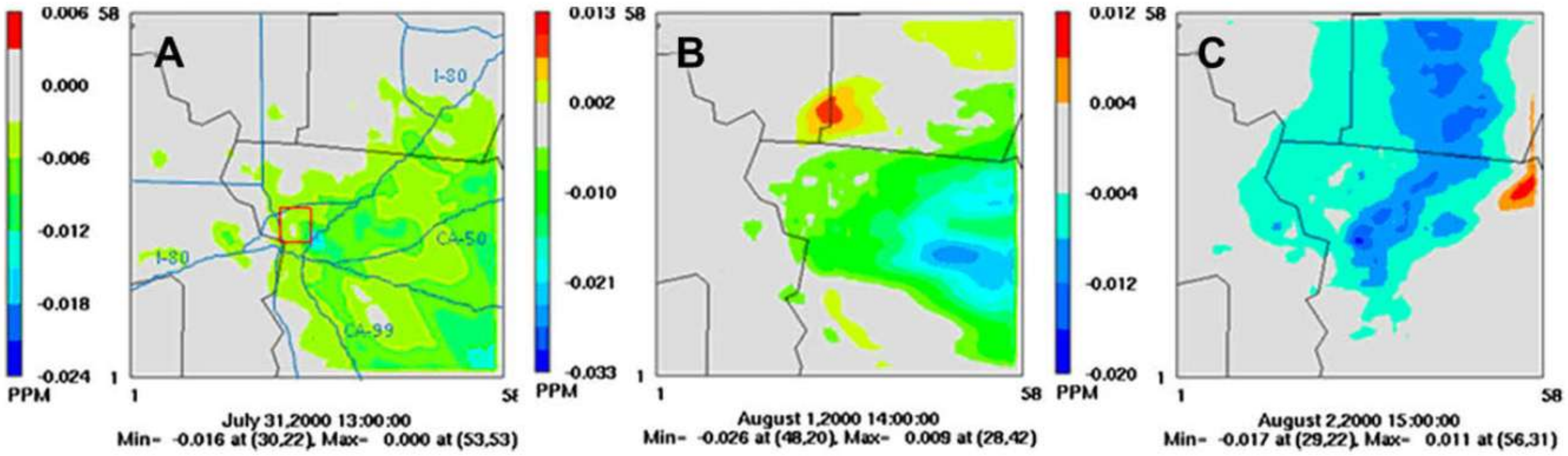
Pros:

- Reduced air temperature slows the photochemical production of pollutants
- Reduced energy consumption offsets emissions of greenhouse gases and air pollutants from power generation

Cons:

- Reduced vertical mixing depresses planetary boundary layer height

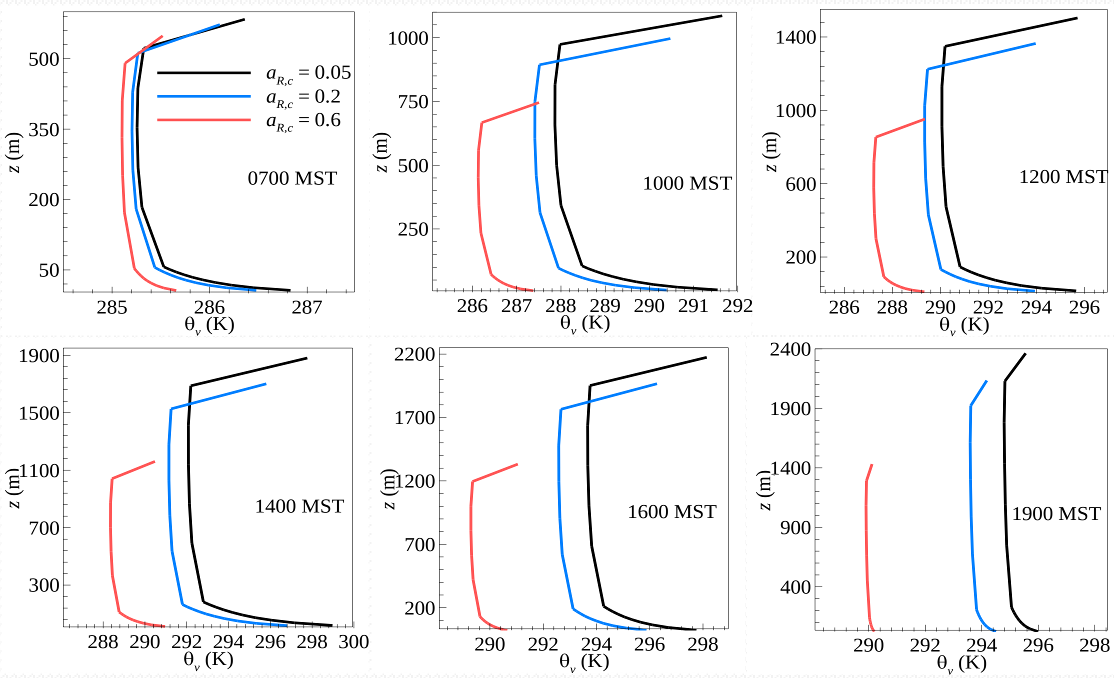
Effect of reflective material on Air quality



Taha et al. 2008. Atmos. Environ.

- Albedo increase: 0.1, 0.25, 0.08 for roof, wall and ground
- Study area and time: Sacramento, summer of year 2000
- Ozone concentration is decreased for most of the study area

Effect of reflective material on Air quality



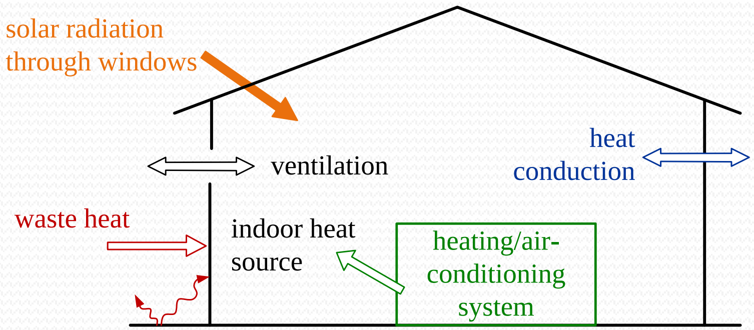
Song and Wang. 2014. Boundary-layer Meteoro.

- Planetary boundary layer (PBL) height decreases with roof albedo across the day
- Maximum reduction of PBL height is about 40% at 1900 MST
- Reduced height indicates a higher concentration of pollutants in PBL

Discussion

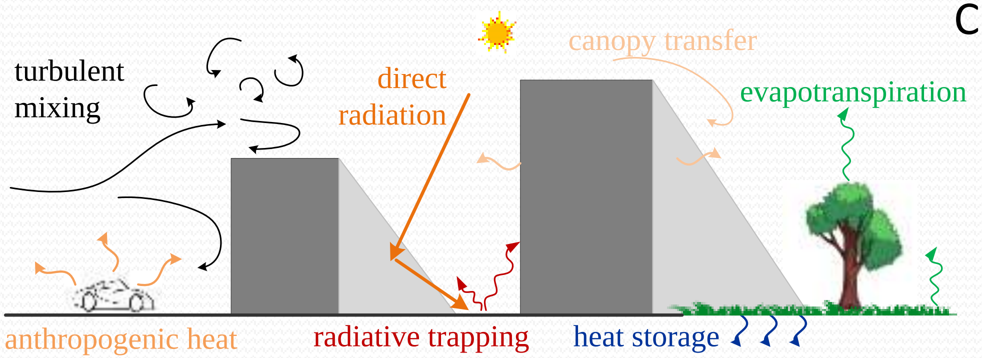
1. Scale effect
2. Geographical and meteorological conditions
3. Uncertainty and variability of models
4. Alternative strategies for UHI mitigation

Scale effect



Building scale (10 – 10^2 m)

City scale (10^3 – 10^4 m)



Neighborhood scale (10^2 – 10^3 m)

Discussion

1. Scale effect

2. Geographical and meteorological conditions
    a) Calm wind condition vs. strong wind condition
    b) Inland city vs. costal city
    c) Low-latitude area vs. high-latitude area

3. Uncertainty and variability of models

4. Alternative strategies for UHI mitigation

Discussion

1. Scale effect

2. Geographical and meteorological conditions

3. Uncertainty and variability of models
   a) Variability of model setup and assumption
   b) Uncertainty in meteorological forcing from measurement and prediction

4. Alternative strategies for UHI mitigation

Discussion

1. Scale effect

2. Geographical and meteorological conditions

3. Uncertainty and variability of models

4. Alternative strategies for UHI mitigation
   a) Green roofs
   b) Permeable pavements
   c) Tree and shading
   d) Phase-changing materials

Concluding remarks

- Complex interactions of many urban environmental factors
- The need of further research efforts for field measurements
- City by city optimal strategy instead of "one-solution-fits-all"

Question?