
Recent Progress on Urban Heat Mitigation Technologies
M. Santamouris
UNSW Sydney, Australia

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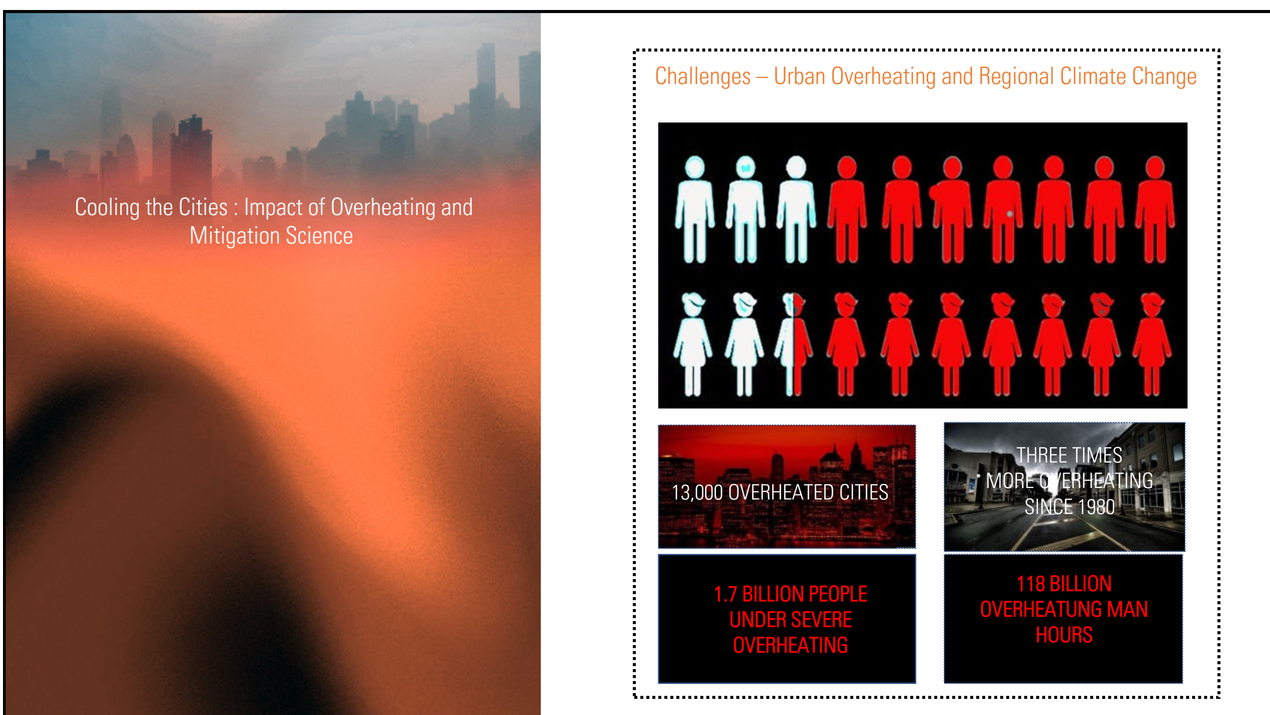
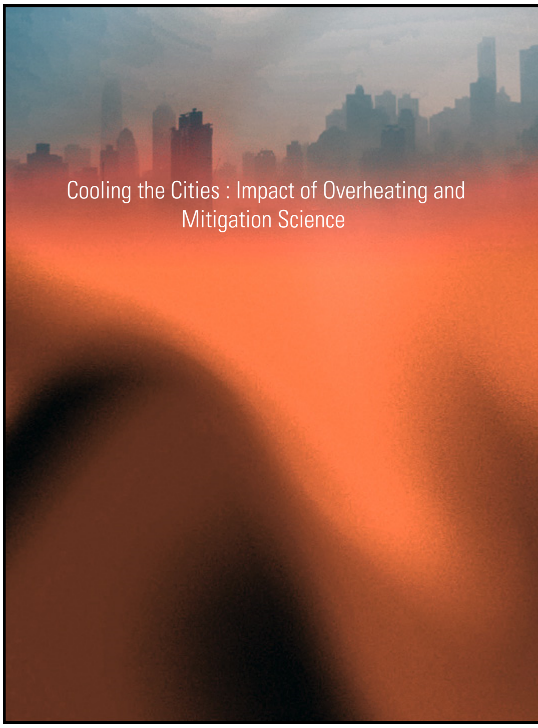
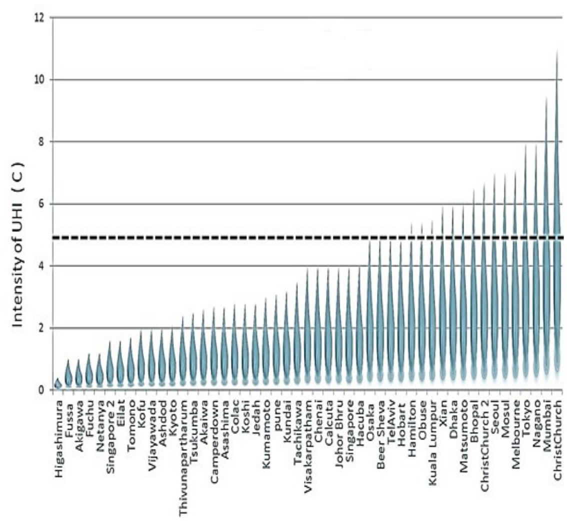

Cooling the Cities : Impact of Overheating and Mitigation Science
Challenges – Urban Overheating and Regional Climate Change
13,000 OVERHEATED CITIES
THREE TIMES MORE OVERHEATING SINCE 1980
1.7 BILLION PEOPLE UNDER SEVERE OVERHEATING
118 BILLION OVERHEATUNG MAN HOURS

2



Challenges – Urban Overheating and Regional Climate Change



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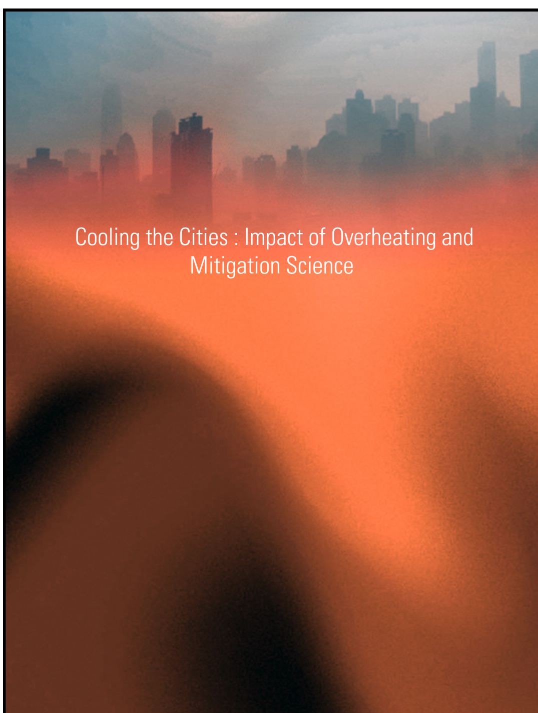
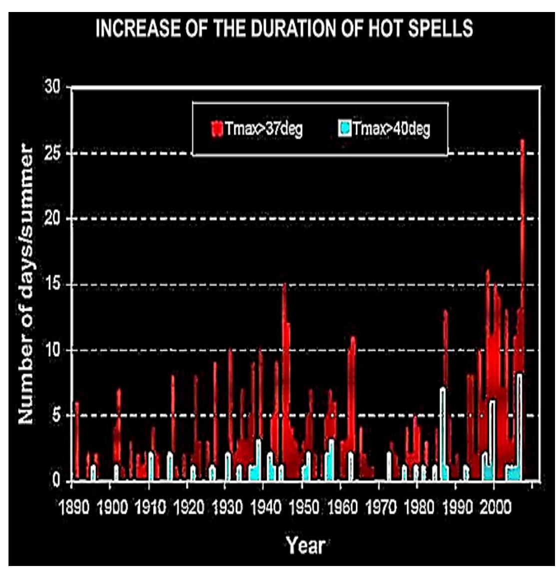


Challenges – Urban Overheating and Regional Climate Change



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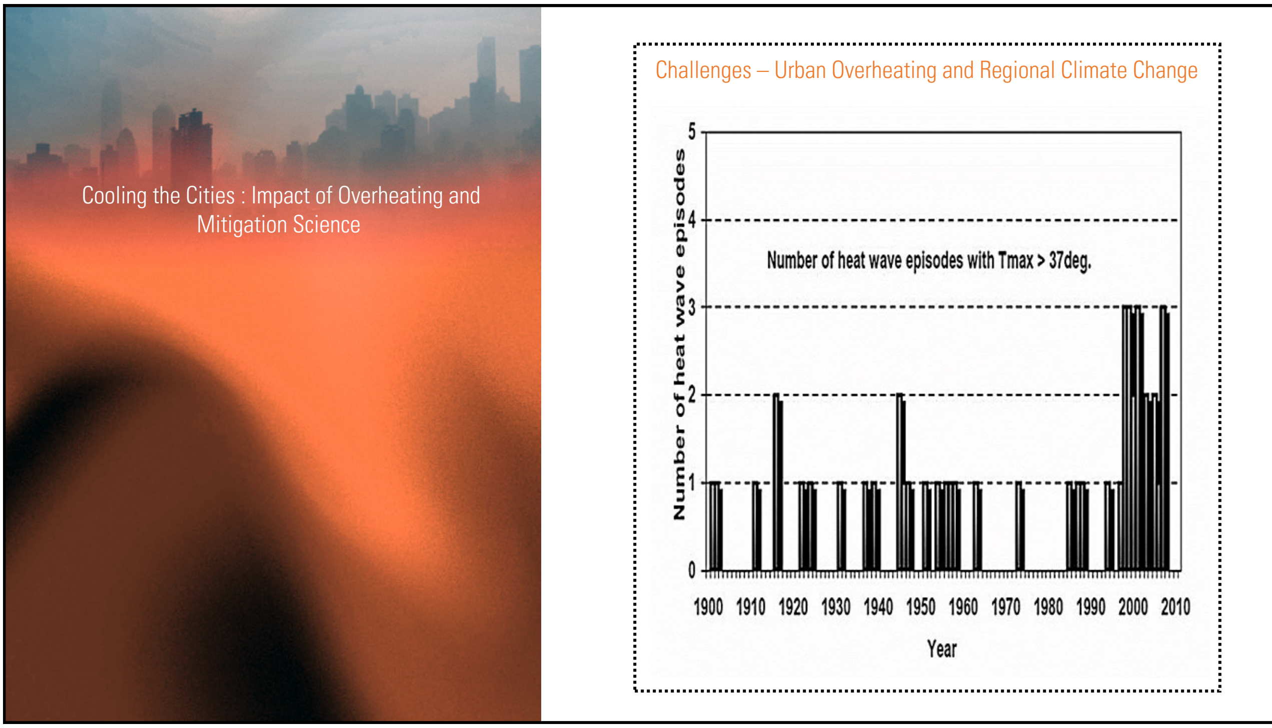
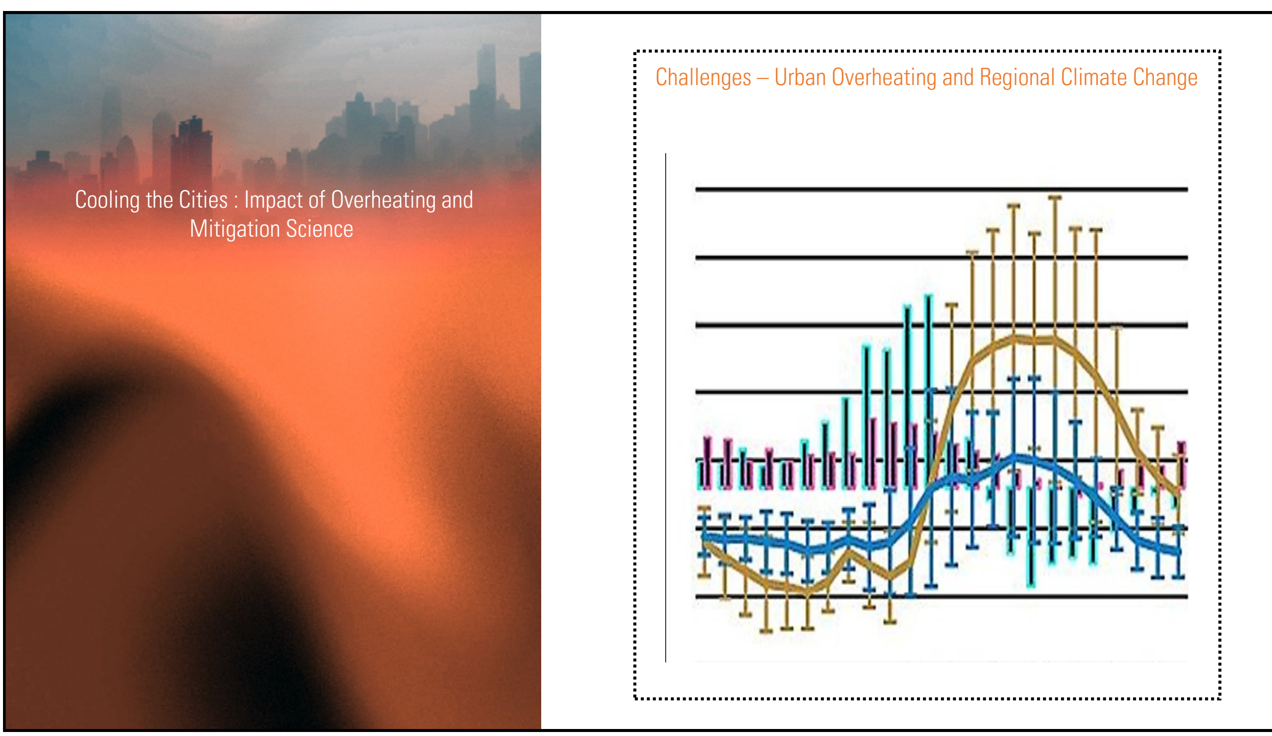

Cooling the Cities : Impact of Overheating and Mitigation Science
Challenges – Urban Overheating and Regional Climate Change
Number of heat wave episodes with Tmax > 37deg.
Number of heat wave episodes
0
1
2
3
4
5
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Year

5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Challenges – Urban Overheating and Regional Climate Change

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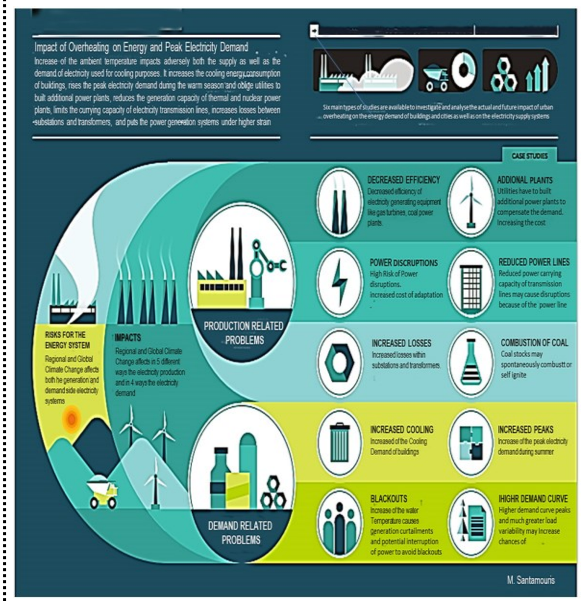
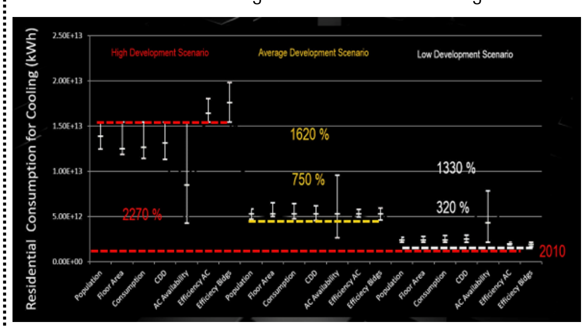
Cooling the Cities : Impact of Overheating and Mitigation Science

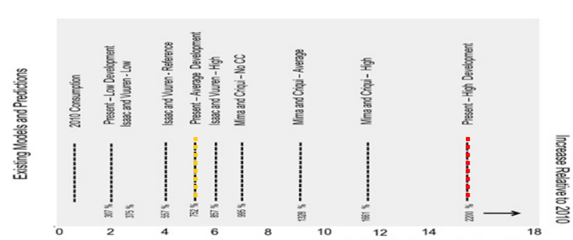
Urban Overheating and Local Climate Change

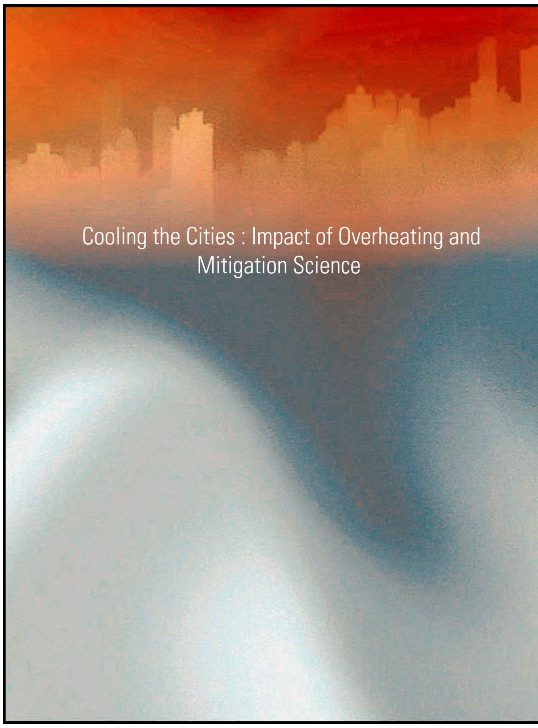


Cooling the Cities : Impact of Overheating and Mitigation Science

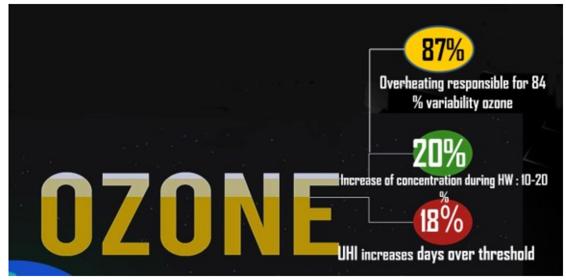
Urban Overheating and Local Climate Change

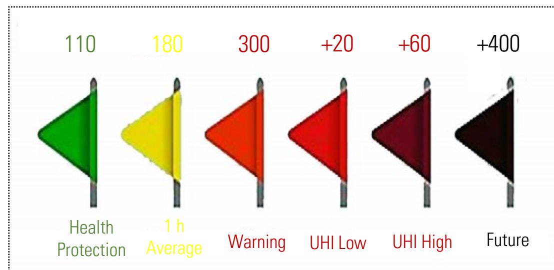






Urban Overheating and Local Climate Change





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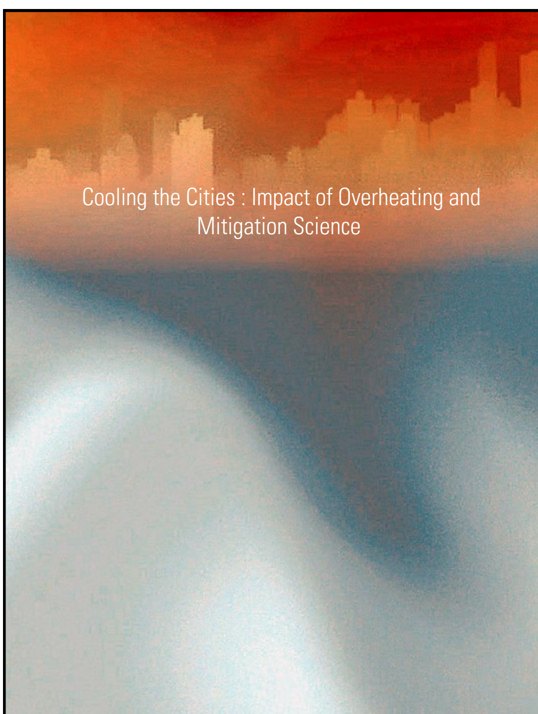
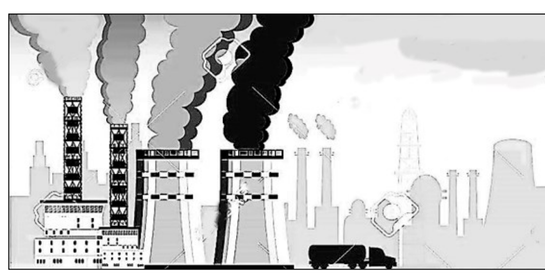


Urban Overheating and Local Climate Change



3.32%/°C ± 0.36%/°C increase in CO_2 emissions,

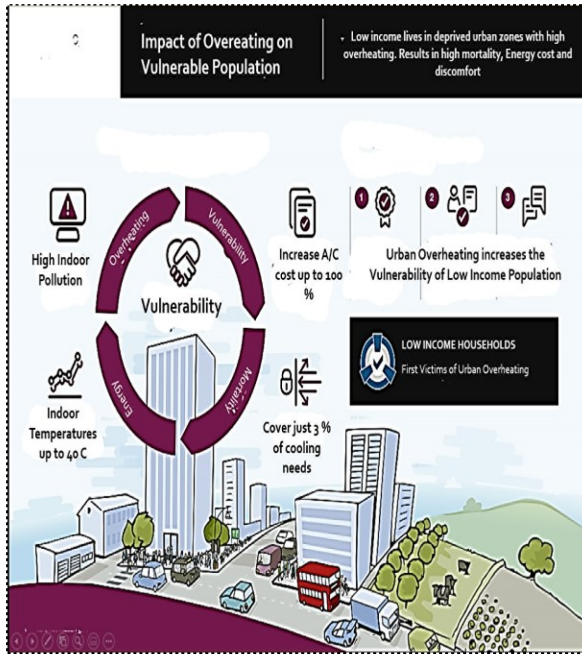
3.35%/°C ± 0.50%/°C increase in SO_2 emissions,

and

3.60%/°C ± 0.49%/°C increase in NO_X emissions

10

Cooling the Cities : Impact of Overheating and Mitigation Science



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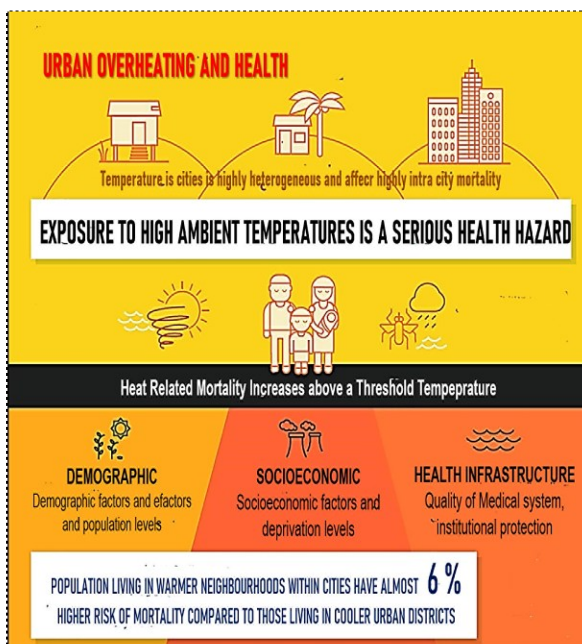

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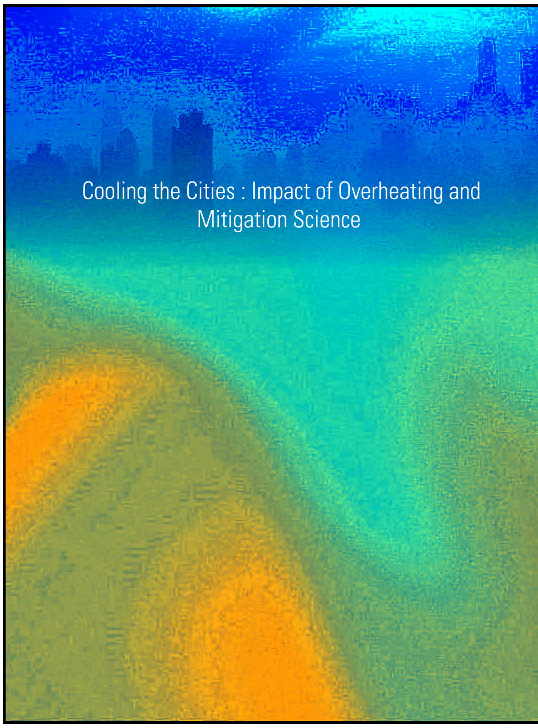
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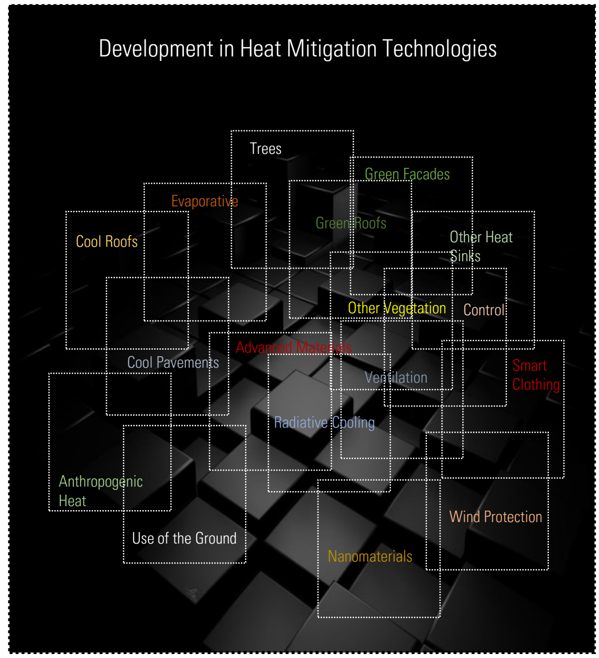
Development in Heat Mitigation Technologies
Trees
Green Facades
Evaporative
Green Roofs
Cool Roofs
Other Heat
Sinks
Other Vegetation
Control
Advanced Materials
Cool Pavements
Smart
Clothing
Ventilation
Radiative Cooling
Anthropogenic
Heat
Wind Protection
Use of the Ground
Nanomaterials

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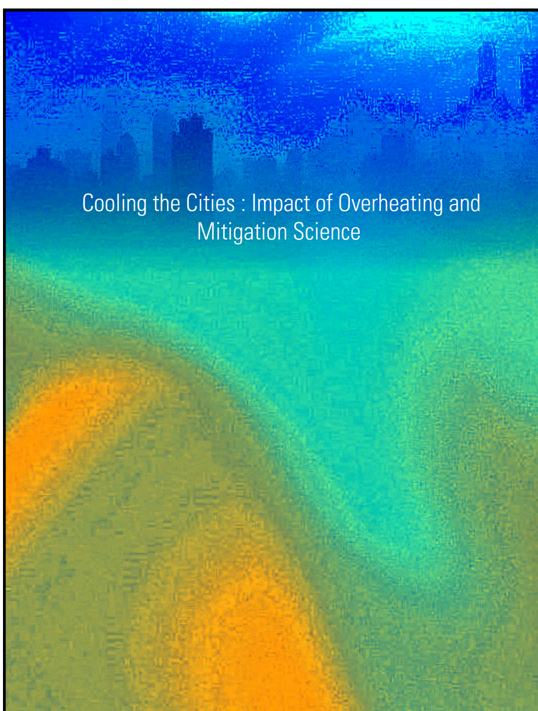
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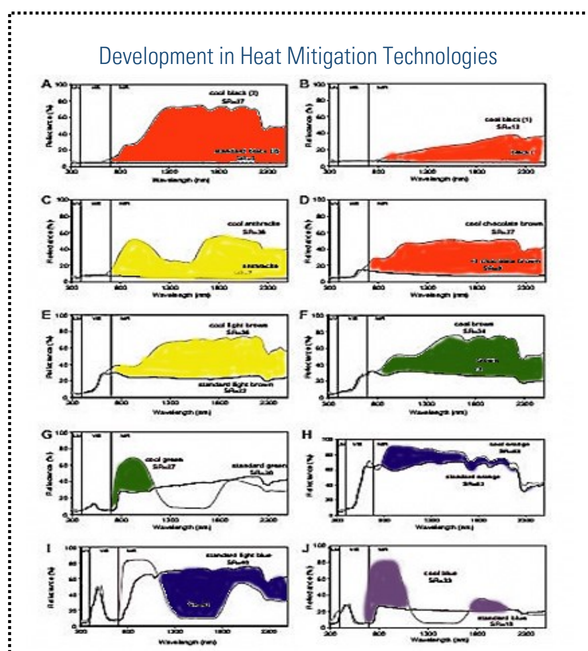
Development in Heat Mitigation Technologies
A
B
C
D
E
F
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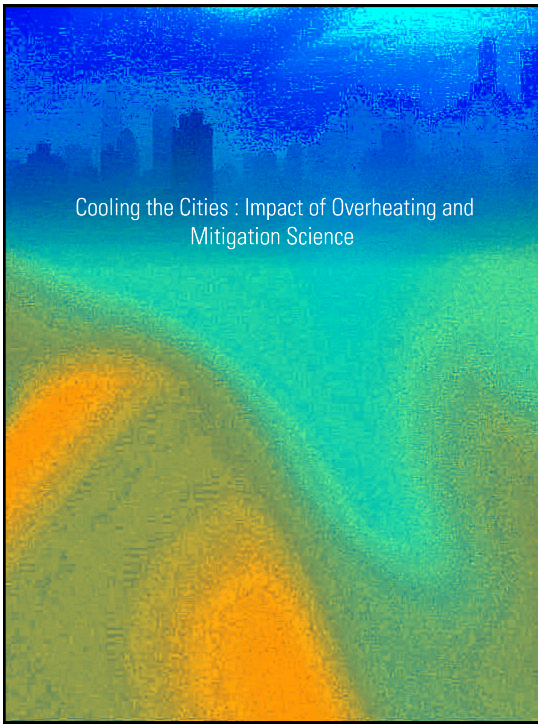
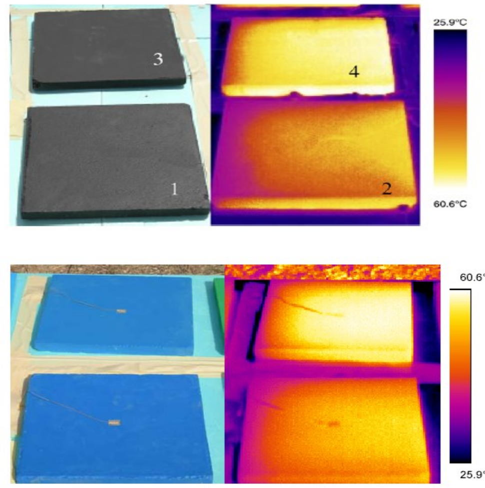
H
I
J

14



Development in Heat Mitigation Technologies



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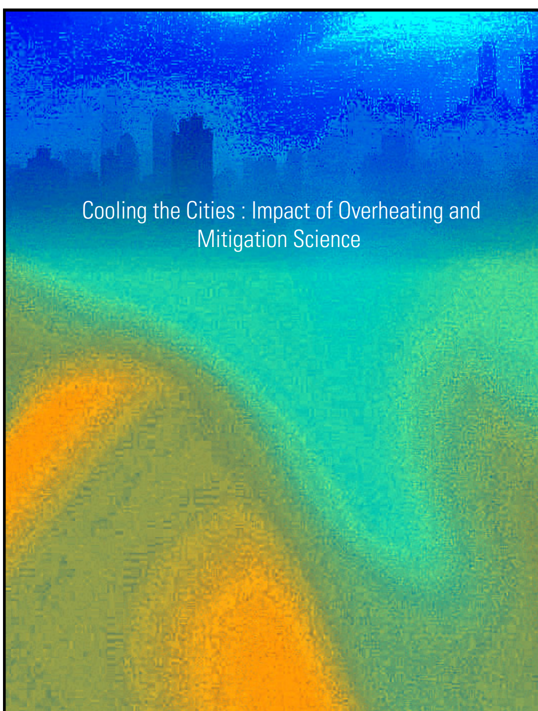
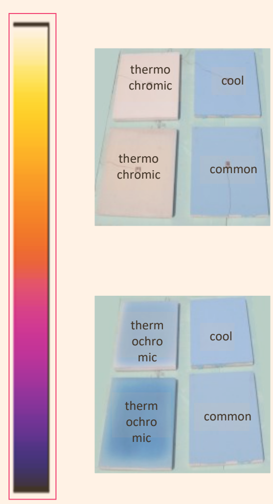


Development in Heat Mitigation Technologies



Thermochromic coatings change color as a function of the ambient temperature.

For low outdoor temperatures (winter), the coatings may be dark presenting a high absorptivity. For higher ambient temperatures (summer), the coating becomes white presenting a high reflectivity. Thus, when applied on roofs or walls they may present the best performance all year round.

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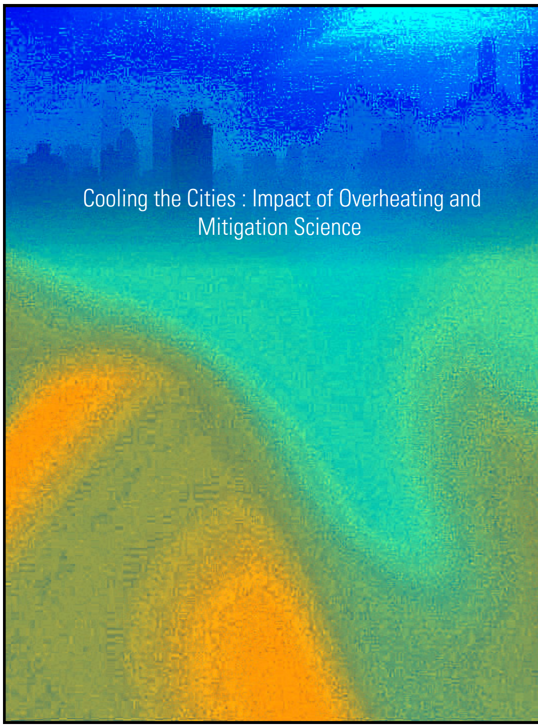
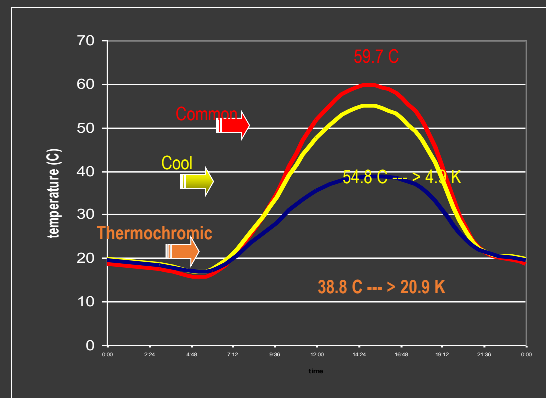
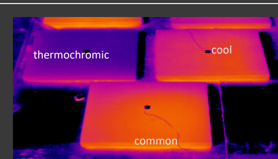


Development in Heat Mitigation Technologies





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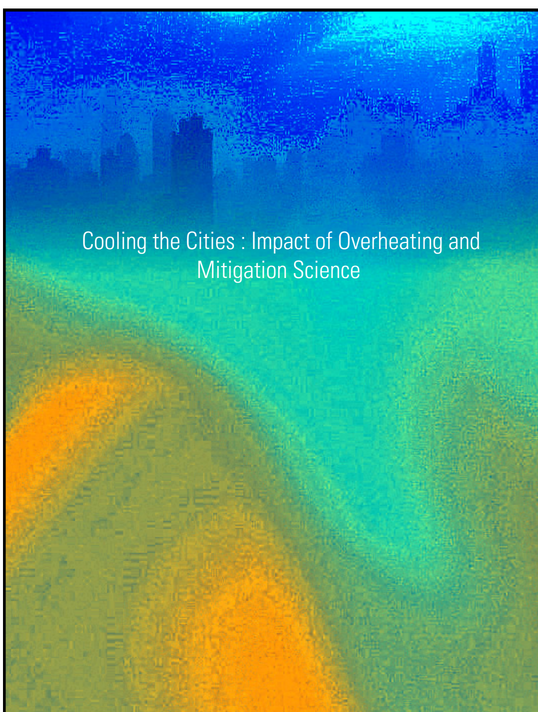
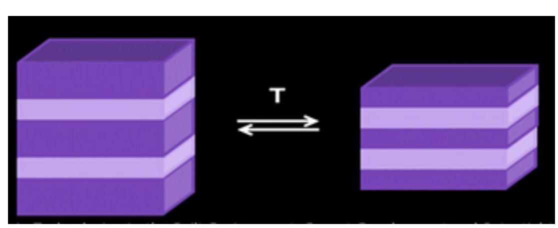


Development in Heat Mitigation Technologies

Thermochromic mechanism of photonic crystals and plasmonics

Thermochromic working mechanism of photonic crystals and plasmonic is based on temperature-sensitive physical or optical property variation of one of their components.

The outstanding feature of nano-scale TC materials compared to their bulk counterparts is the lower rate of photodegradation together with their adjustable temperature-sensitive properties.



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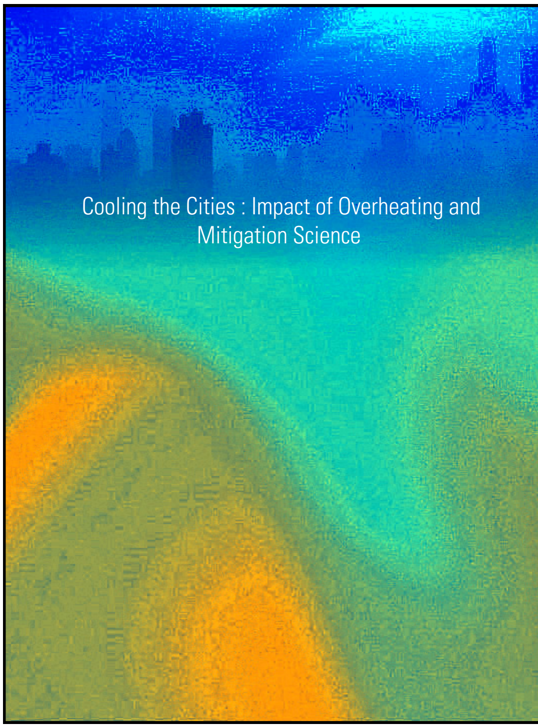
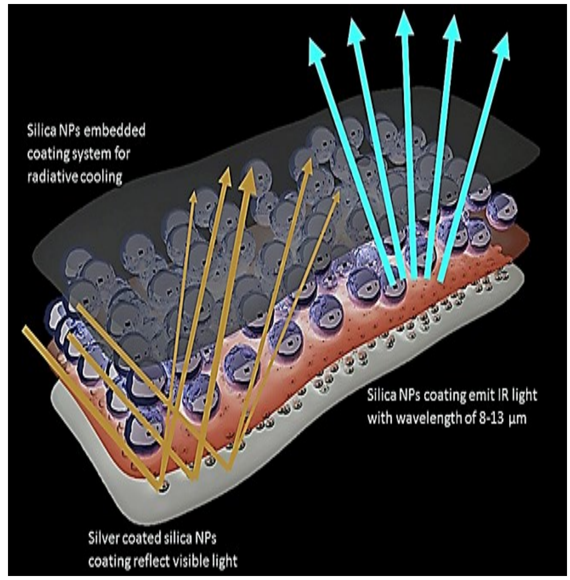
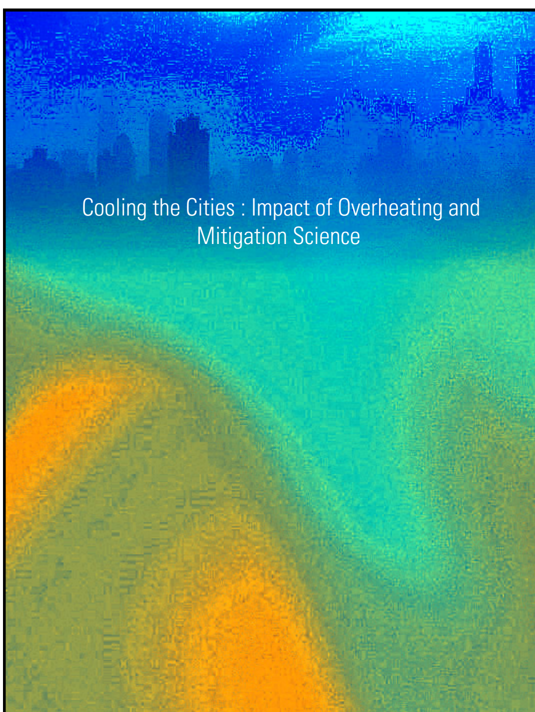


Development in Heat Mitigation Technologies





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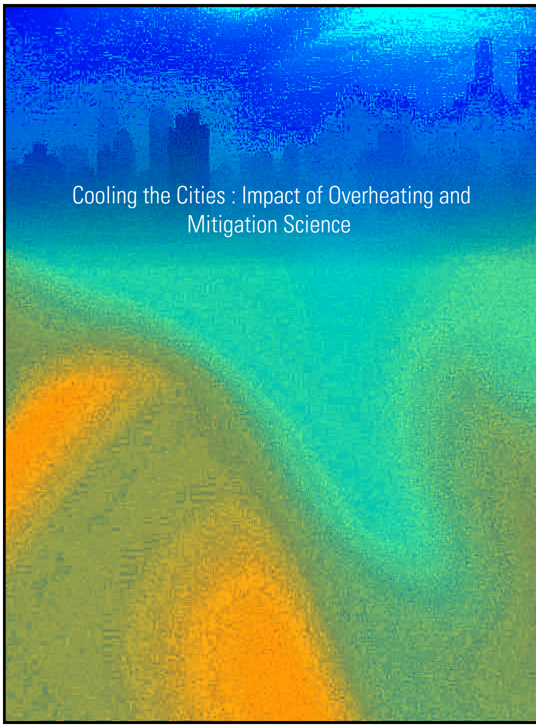
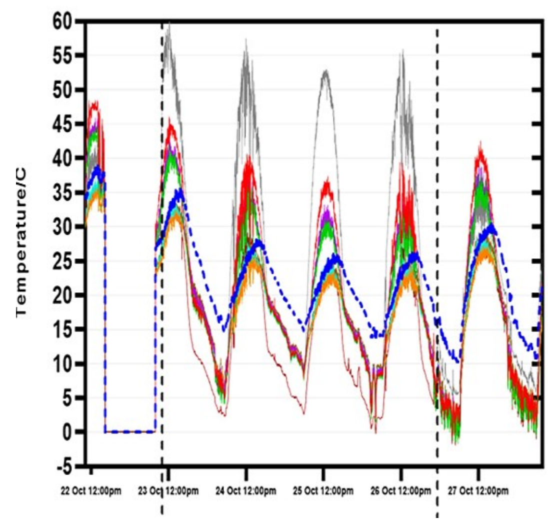
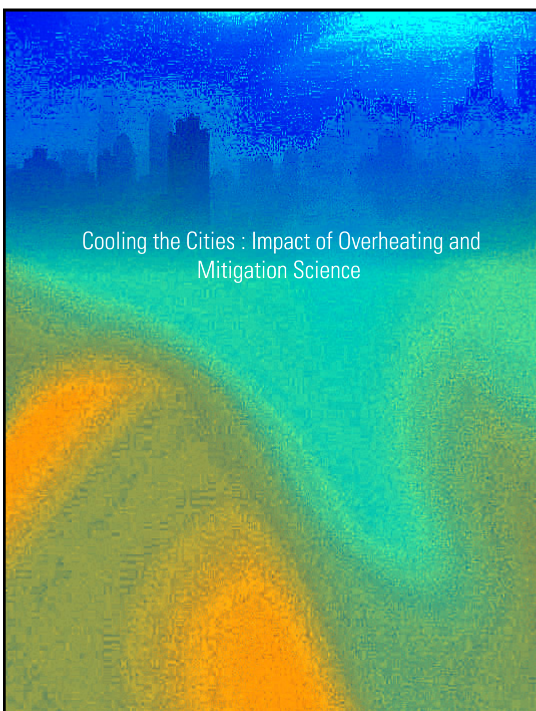
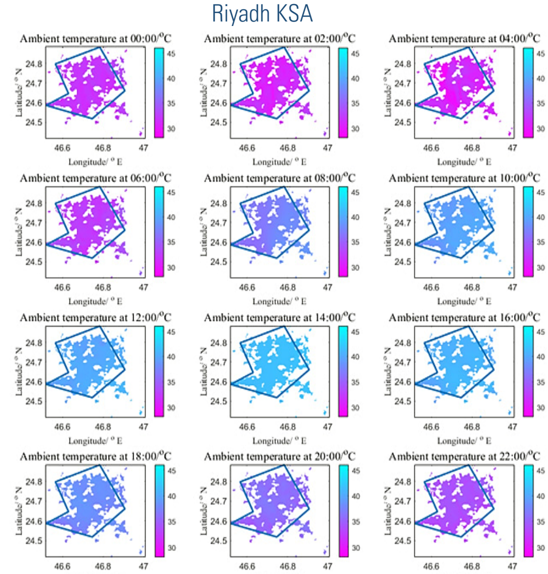


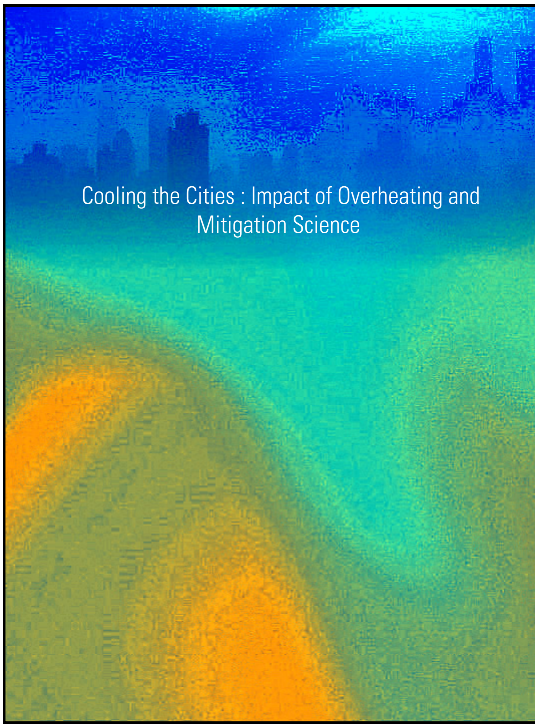
Development in Heat Mitigation Technologies





Development in Heat Mitigation Technologies
Riyadh KSA

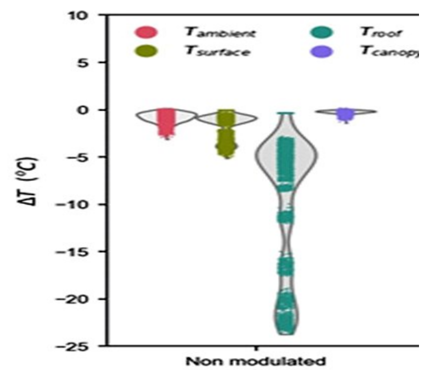




Development in Heat Mitigation Technologies

OVERCOOLING WINTER PROBLEMS

Use of SCM may decrease the ambient temperature up to 2 C
Results of WRF simulations for Kolkata India



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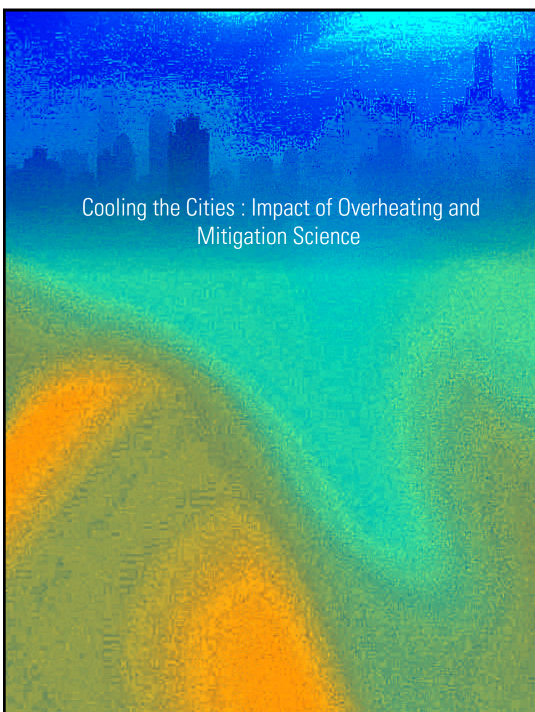
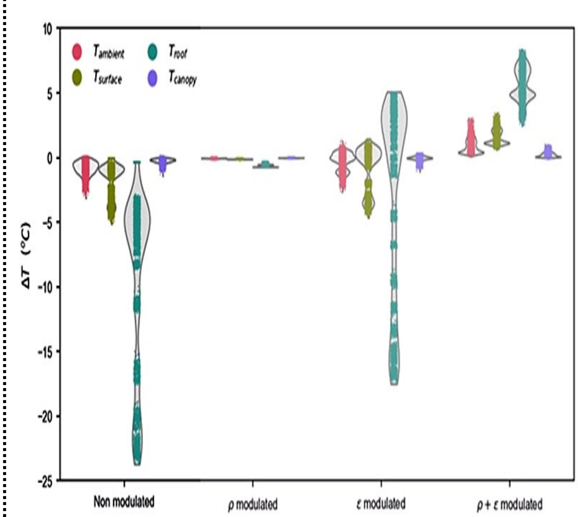


Development in Heat Mitigation Technologies



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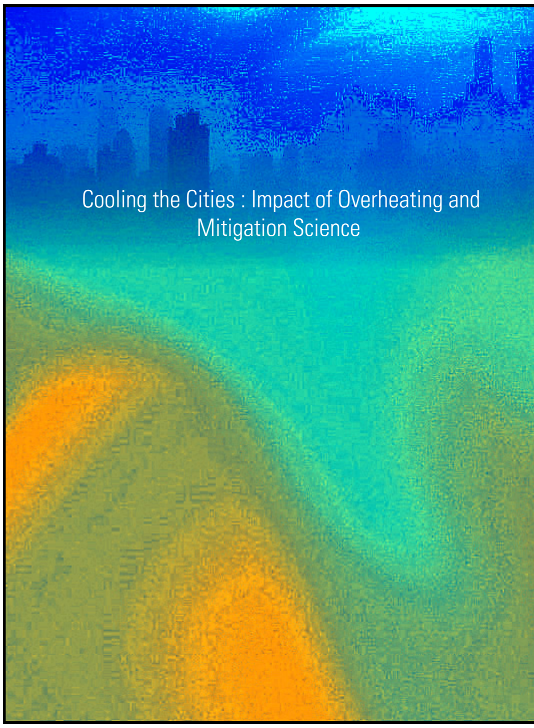
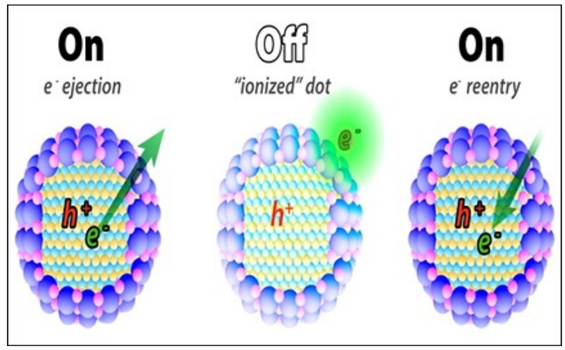
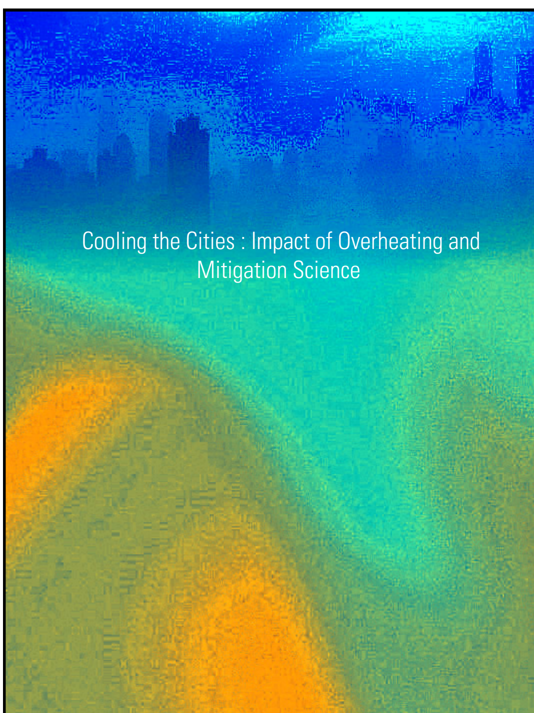


Development in Heat Mitigation Technologies

Quantum dots (QD) are very small semiconductor particles, only several nanometers in size, so small that their optical and electronic properties differ from those of larger particles. They are a central theme in nanotechnology. Many types of quantum dot will emit light of specific frequencies if electricity or light is applied to them, and these frequencies can be precisely tuned by changing the dots' size, shape and material, giving rise to many applications.





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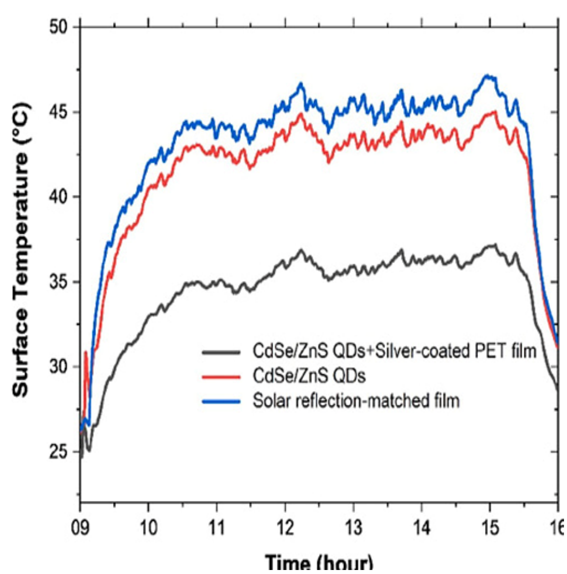
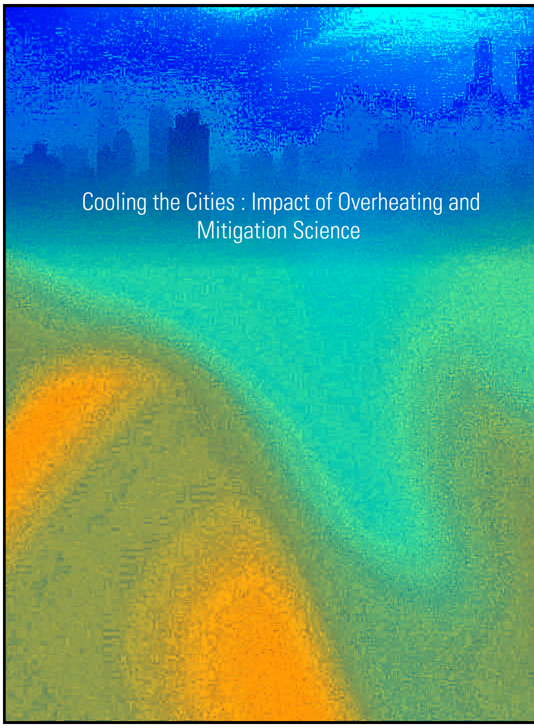
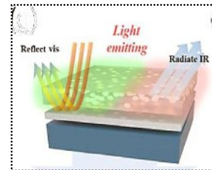


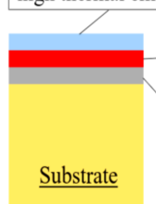


Development in Heat Mitigation Technologies

Coloured Super Cool Materials



Top layer: Thermal emitter component - Thermal emitter material with high solar transmission (300-2500 nm) and high thermal emission (8-13 µm)



Mid layer: Solar reflective component - layer 1: non-thermal emitter (fluorescent) material (white/metallic or non-white/non-metallic) with fluorescence in (300 nm-λ_{AE}) and high light transmission in (λ_{AE} -2500 nm)

Base layer: Solar reflective component - layer 2: Reflective material with high solar reflection in (λ_{AE} -2500 nm)

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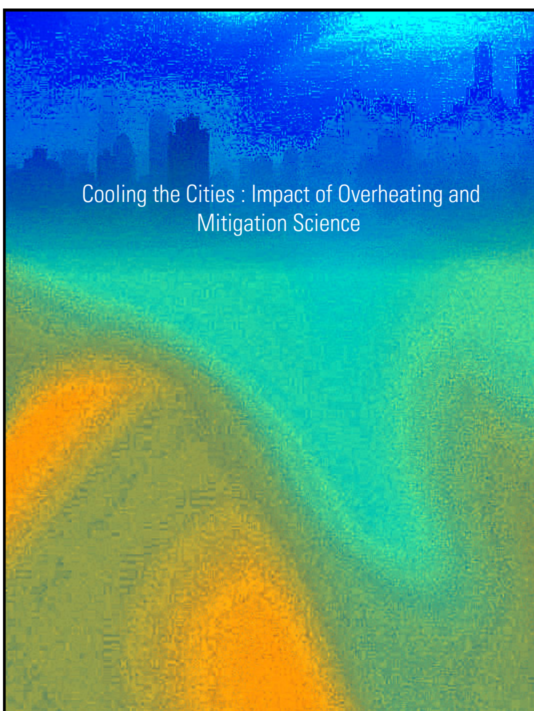

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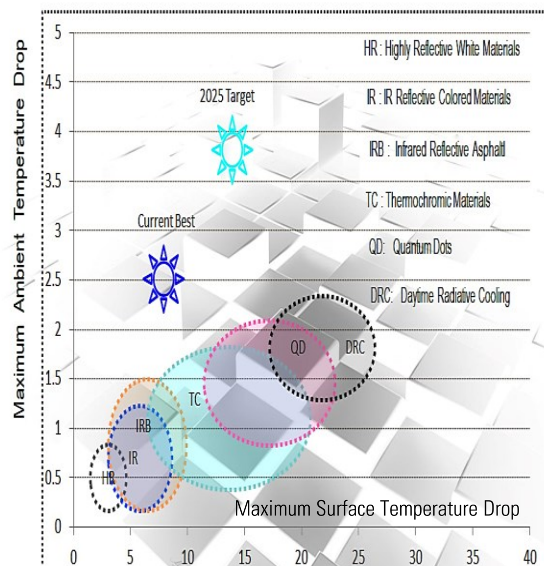

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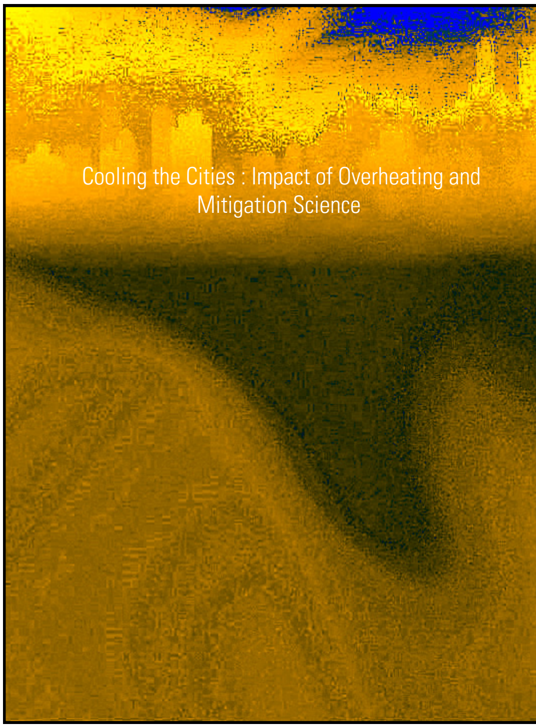
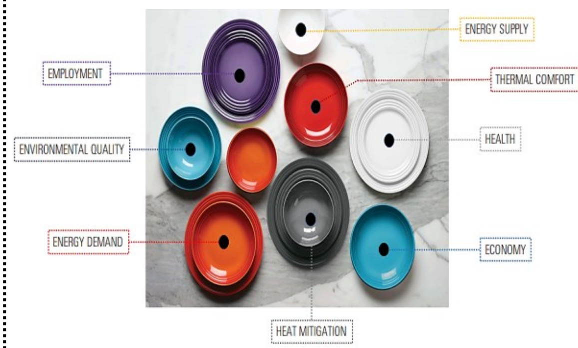


Impact of Heat Mitigation Technologies



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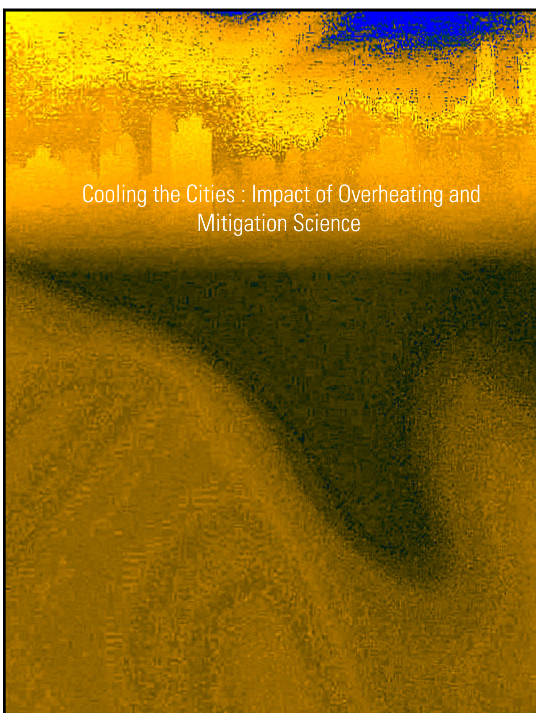
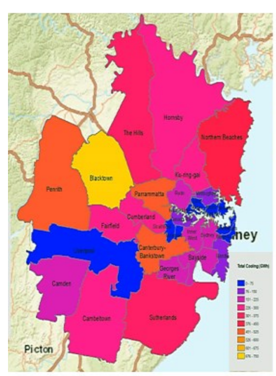
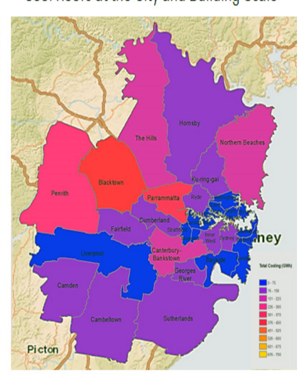


Energy Impact of Heat Mitigation Technologies

Reference



Cool Roofs at the City and Building Scale

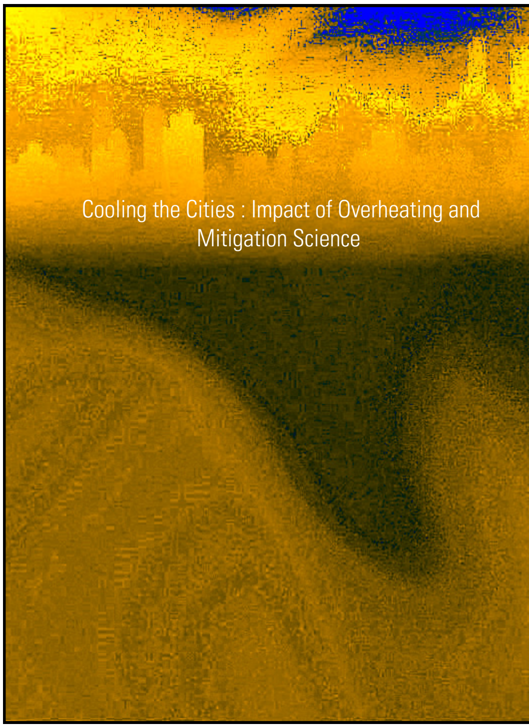


Total Cooling Consumption Residential and Commercial Buildings : 6300 GWh

Total Cooling Consumption Residential and Commercial Buildings : 3260 GWh

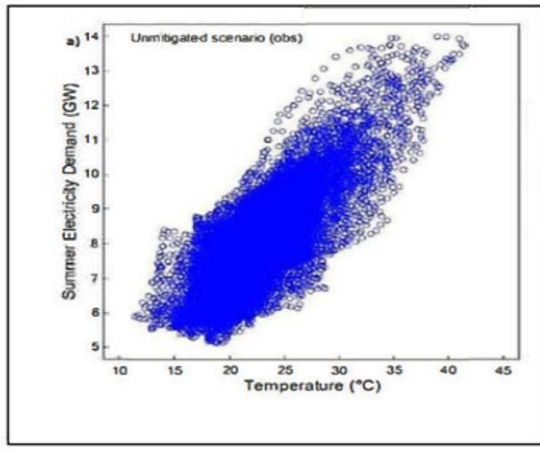
49 %

30



Energy Benefits Heat Mitigation Technologies

Potential decrease of the peak hourly cooling demand caused by the implementation of cool roofs



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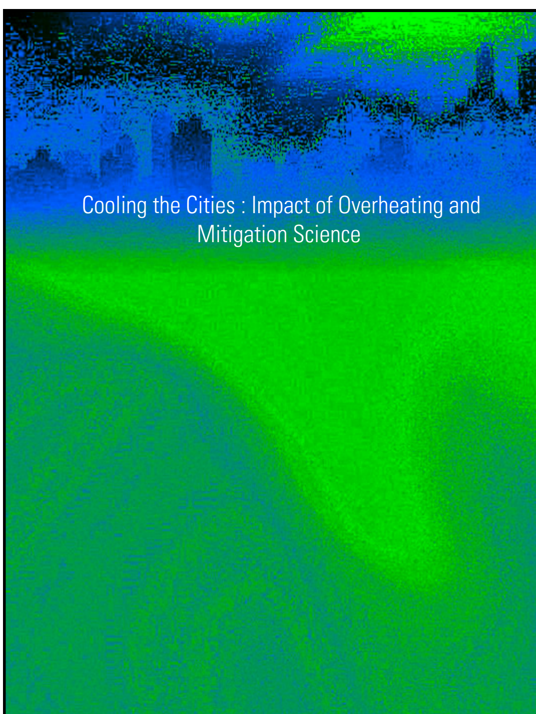
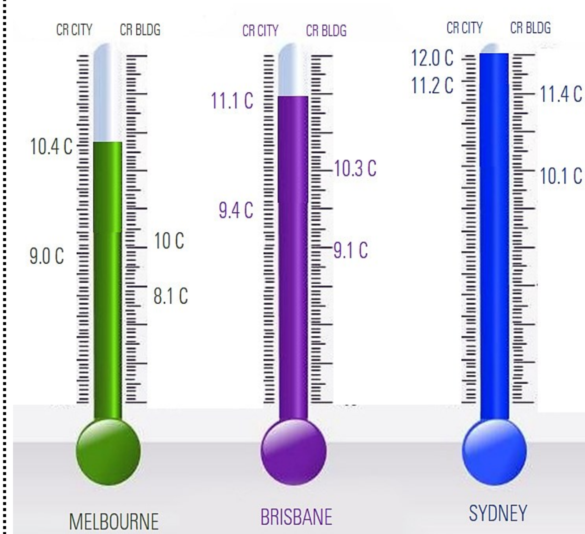


Environmental and Other Benefits of Heat Mitigation Technologies

Reduction of the maximum indoor air temperature _low-rise office without roof insulation



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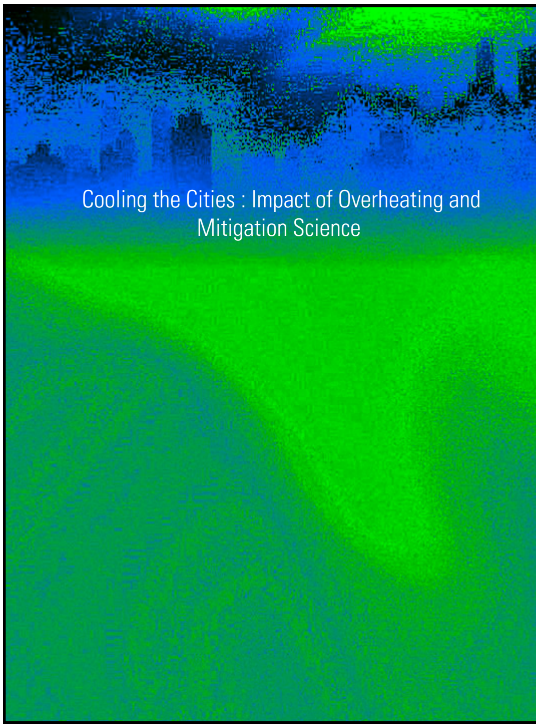
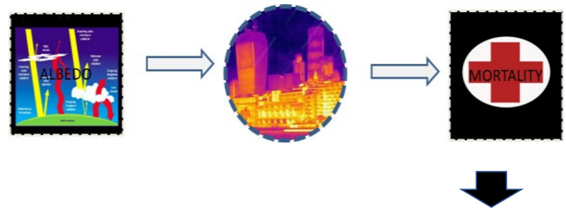


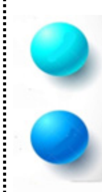
Environmental and Other Benefits of Heat Mitigation Technologies

0.1 increase albedo

Decrease 0.09 C 17 PM Temp

Drop 0.1 to 4 deaths per day





An average decrease of deaths close to 19.8% per degree of temperature drop,

About 1.8% decrease of mortality per 0.1 increase of the albedo

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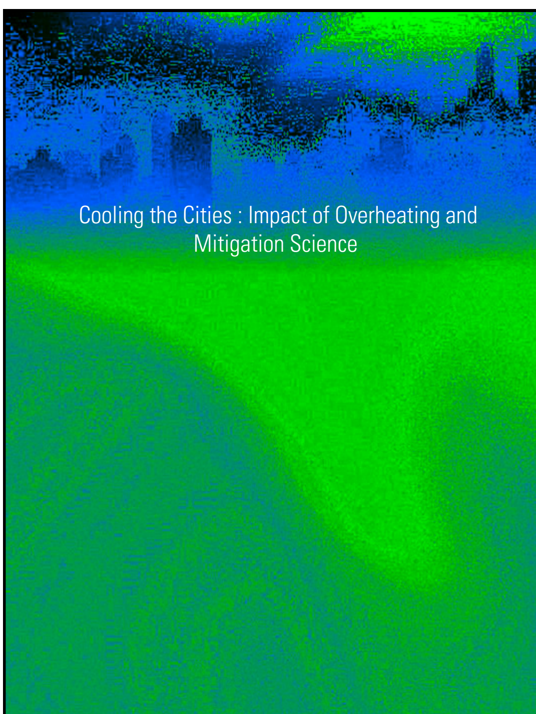
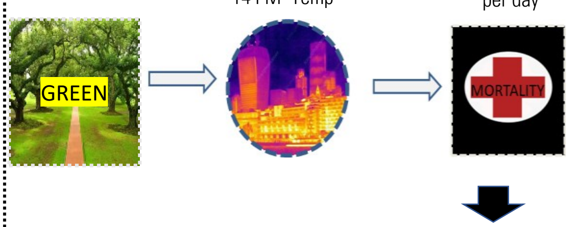


Environmental and Other Benefits of Heat Mitigation Technologies

Increase GI

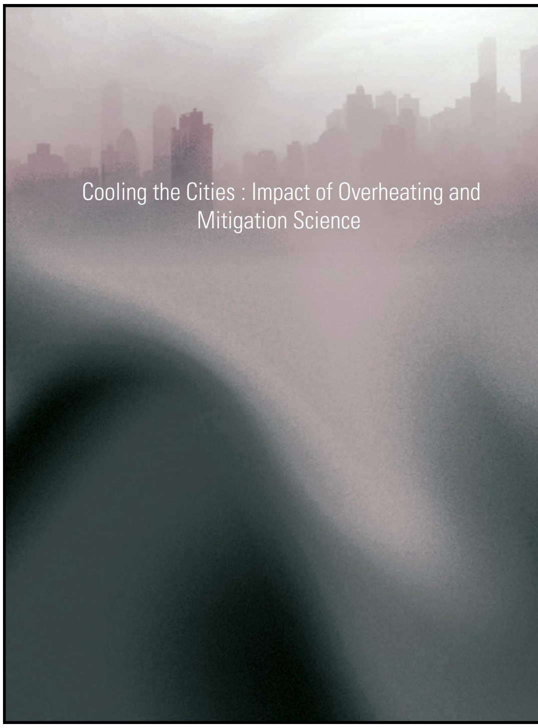
Decrease 14 PM Temp

Drop of deaths per day

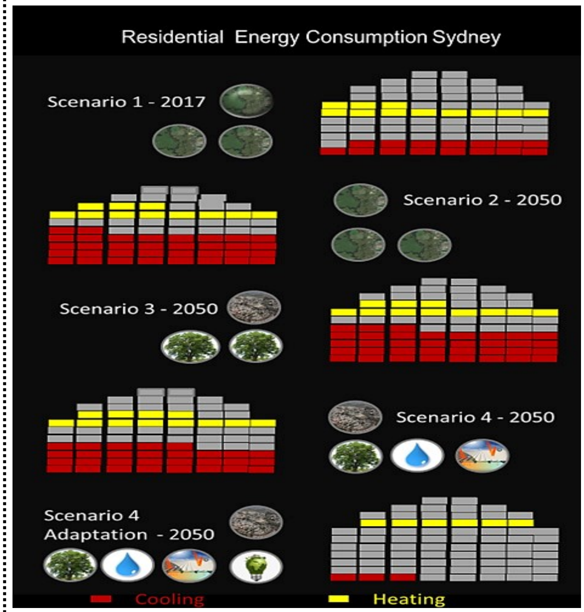


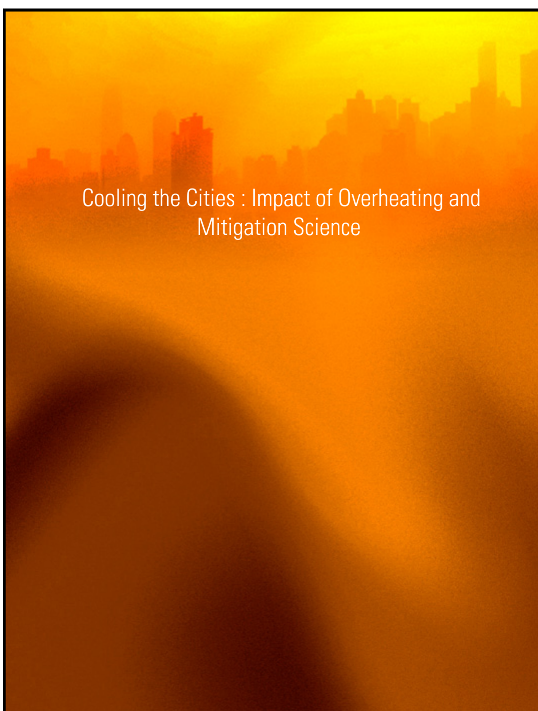
Drop of the peak temperature by 0.1 C corresponds to 3 % decrease of mortality

34

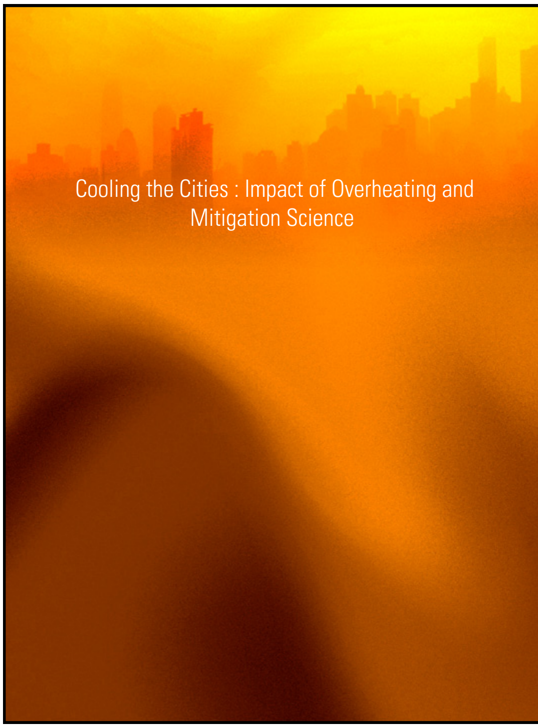


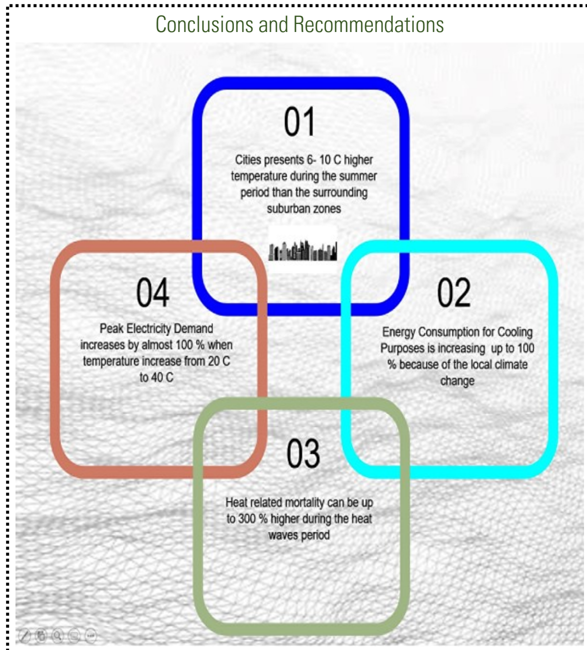
Future Forecasts

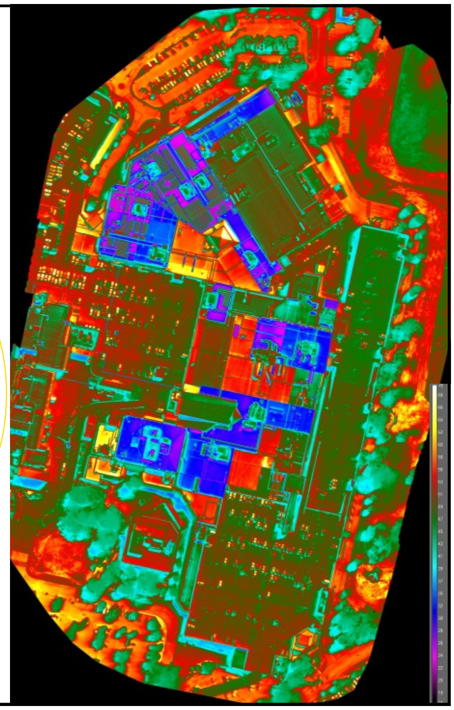




Conclusions and Recommendations


Cooling the Cities : Impact of Overheating and Mitigation Science


Conclusions and Recommendations
01
Cities presents 6- 10 C higher temperature during the summer period than the surrounding suburban zones
02
Energy Consumption for Cooling Purposes is increasing up to 100 % because of the local climate change
03
Heat related mortality can be up to 300 % higher during the heat waves period
04
Peak Electricity Demand increases by almost 100 % when temperature increase from 20 C to 40 C



Results of the Cool Roofs Study in Australia

Riccardo Paolini, UNSW

Infrared aerial orthophoto of Shellharbour Stockland Shopping Centre
CRC LCL Project RP1037

1

Research questions of this talk

- Can supercool materials contribute to urban heat mitigation and building ventilation?
- What mechanisms are involved, and how can we exploit them?

(why are we talking about radiation in a ventilation webinar?)

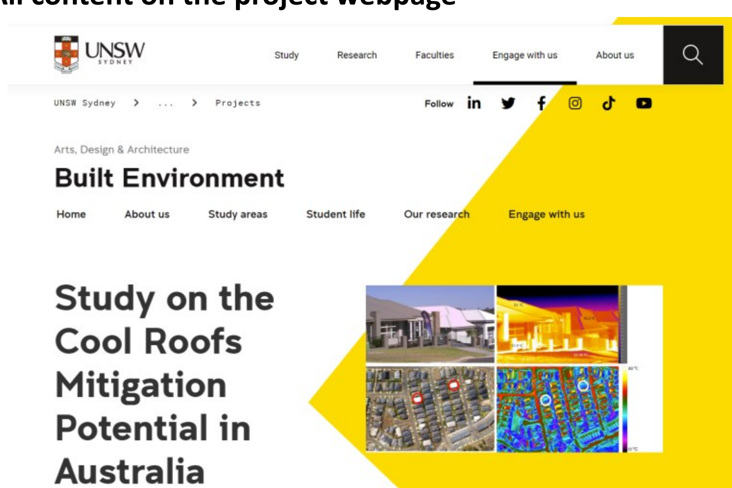
Field-applied cool roof coating on a commercial building in Victoria (source: energystar.com.au).

2

Project Team

DISER (Dept of Industry, Science, Energy and Resources, Australian Government)	UNSW	Partner Investigators
Stanford Harrison Tanya Kavanagh Kat Hamilton Kavya Koonampilli	Prof M Santamouris Dr R Paolini Dr S Garshasbi Dr J Feng Dr S Arasteh Dr S Haddad Dr Afroditi Synnefa Dr K Gao Prof D Prasad A/Prof L Ding A/Prof P Osmond	Dr C Bartesaghi-Koc (Uni of Adelaide) Prof D Kolokotsa (TUC, Greece) Dr Ansar Khan (Uni of Kolkata, India) Kurt Shickman (GCCA, USA) Prof A Papadopoulos (AUTH, Greece)

All content on the project webpage



https://www.unsw.edu.au/arts-design-architecture/our-schools/built-environment/our-research/clusters-groups/high-performance-architecture/projects/study-on-the-cool-roofs-mitigation-potential-in-australia

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On the energy impact of cool roofs in Australia

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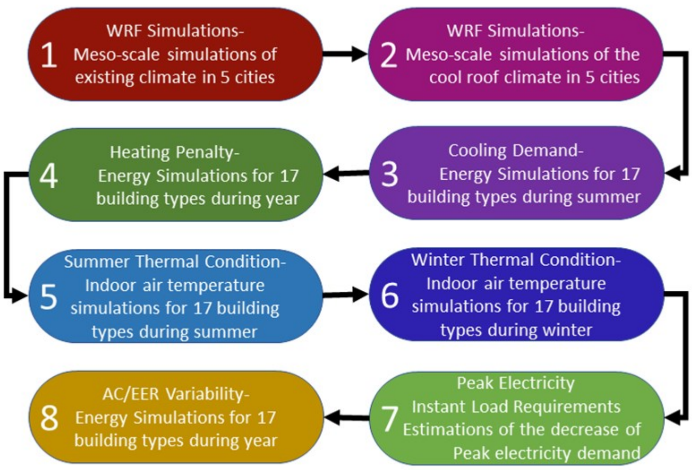
Free access until 31 Dec 2022 https://authors.elsevier.com/c/1g3-R1M7zH8bgy

Project scope

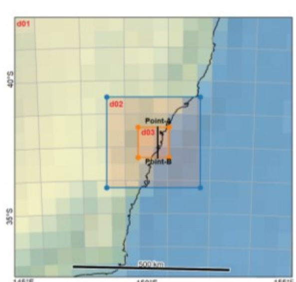
1. Technology and market overview in Australia and overseas
2. Performance of cool roofs in Australian climate zones considering
   - Urban heat mitigation
   - Cooling energy savings in commercial and residential buildings, existing and new (NCC2019)
   - Cost-benefit analysis
3. Identification of barriers for the use of cool roofs (in view of NCC2025)
4. Industry needs and perspectives

Project Roadmap

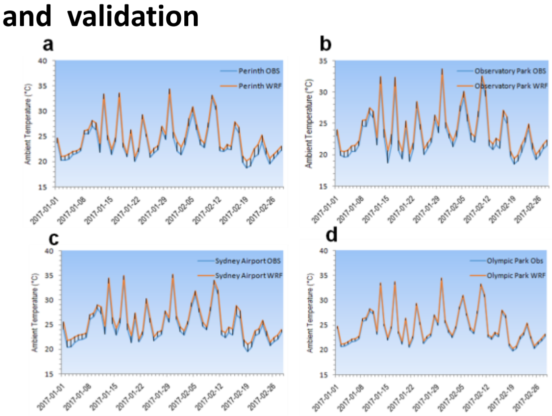


Garshasbi et al. (2023) https://doi.org/10.1016/j.enbuild.2022.112577

ARF-WRF 4.3 model and validation



500 m x 500 m in the inner domain



Parameters	Local weather stations			
	Penrith	*Observatory Hill*	*Sydney Airport*	*Olympic Park*
Correlation coefficient	0.975	0.981	0.986	0.985
Mean Bias error (°C)	0.352	0.932	0.429	0.563
Mean absolute error (°C)	0.523	0.926	0.432	0.501

Selected Buildings

Building performance simulations of 17 existing (pre-code) and new typical buildings, low-rise and high-rise, of different categories:

- Office
- Retail (shopping centre)
- School
- House
- Apartment buildings

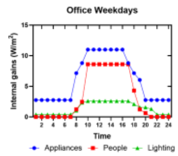
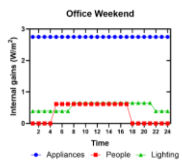
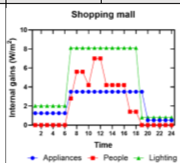
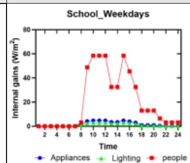
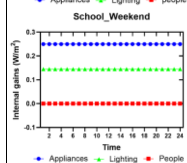
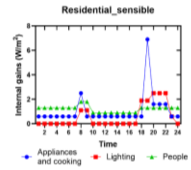
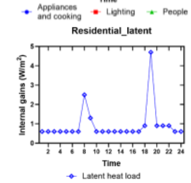
Building archetypes from a previous study carried out by DISER

Selected Buildings

Roof albedo: 0.15 conventional roof, 0.85 cool roof
Roof thermal emittance: 0.85
Existing (pre-code) buildings: no wall insulation, minimal roof insulation (anti-con blanket).
New buildings: (post-code) NCC 2019 DtS insulation levels, depending on the climate zone.

Building Type	Office			Shopping mall		School	House		Apartment
	Existing uninsulated	Existing w/ roof ins.	New	Existing	New	New	Existing	New	New
Floor area (m^2)	1200			1100		1100	242		624
Window to Wall Ratio (WWR)	0.6			0.3		0.32	0.14	0.15	0.24
Year Built	1990		2018	1990	2018	1990	1990	2018	1990
Number of stories	2 (L)			2 (L)	2 (L)				3 (L)
Low rise (L), mid-rise (M),	-			4 (M)	-	3	1		5 (M)
high-rise (H)	10 (H)			6 (H)	4 (H)				8 (H)
Building height (m)	7.2 (L)			13.8 (L)	13.8 (L)				8.4 (L)
Low rise (L), mid-rise (M),				27.6 (M)		12.6	2.8		14 (M)
high-rise (H)	36 (H)			41.4 (H)	41.4 (H)				22.4 (H)

Occupancy and internal heat gains (NCC / NatHERS)

Building Type	Office			Shopping mall		School	Standalone House		Apartment
	Existing uninsulated	Existing w/ roof ins.	New	Existing	New	Existing	Existing	New	Existing
Intensity of internal heat gains (W/m²) (from NatHERS and NCC 2019)	 					 	 		

Building Performance Simulations

Simulation engine EnergyPlus DesignBuilder SOFTWARE AUSTRALIA

Simulations

1) HVAC in operation

- Ideal HVAC (COP = 1) to compute heating and cooling loads (energy needs)
- Heating setpoint = 20 °C
- Cooling setpoint = 25 °C
- HVAC off out of operation hours (NCC modelling profiles JVc)

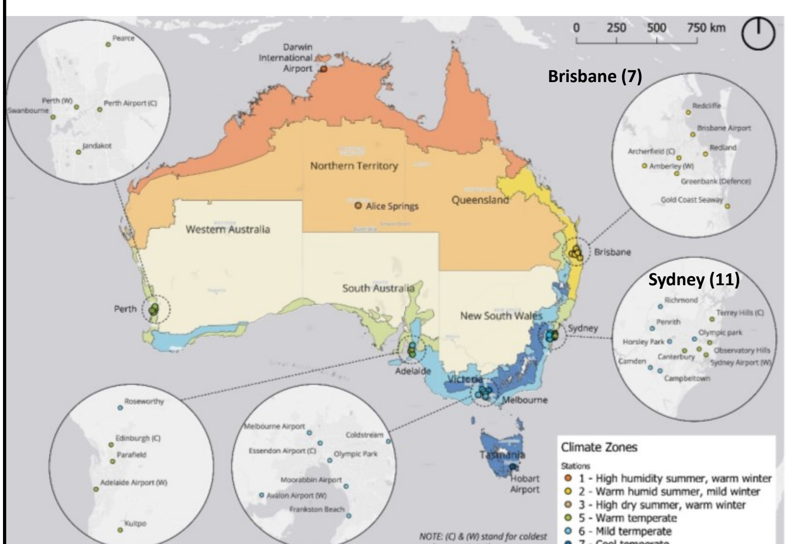
2) Free-floating (no HVAC in operation)

Weather data for building energy simulations

1. Mitigated & unmitigated: 2 summer months (Jan & Feb 2017). Data from climate modelling (WRF)
   - Unmitigated (roofs albedo = 0.15)
   - Heat mitigation with cool roofs (roofs albedo = 0.85)

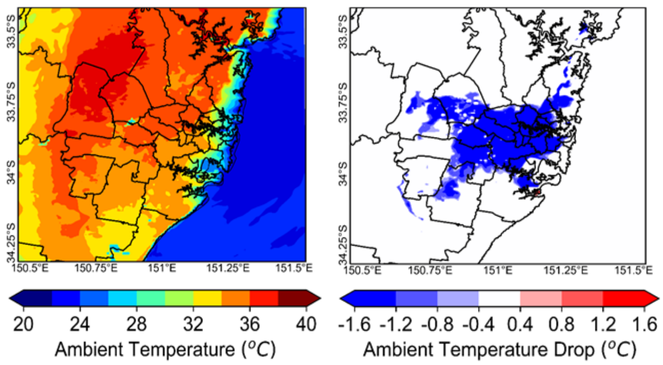
2. Whole year simulations. Data from Bureau of Meteorology (2016-2017)
   - Unmitigated scenario only
   - Weather data from Bureau of Meteorology. Measured solar & infrared radiation data where available; BOM satellite estimated otherwise.
   - Weather data validation with nearby stations

Cities (BOM stations & climate modelling)



Only BOM data:
- Darwin (NT)
- Alice Springs (NT)
- Hobart (Tas)

Results: 2m air temperature (Sydney 14:00– summer day)



Spatial distribution of the ambient temperature and temperature drop in Sydney at 14:00 hrs, caused by the installation of the cool roofs, during a representative summer day.

Greatest temperature drops in built-up areas, not in close proximity to the coast (already cooled by sea breeze).

The temperature drop is not constant across the area.

Some cool roof density is required for temperature drop to occur.

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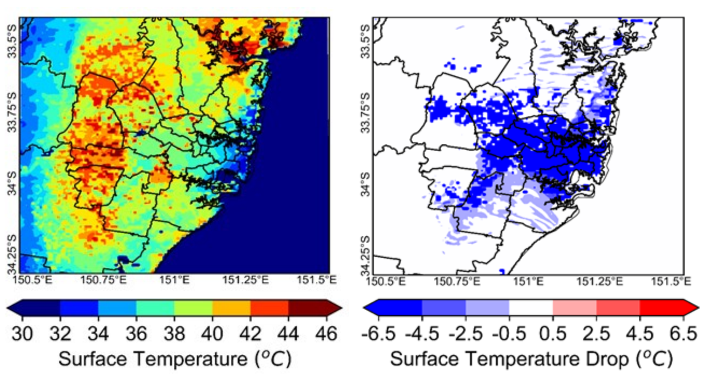
Results: Land Surface Temperature (Sydney 14:00 summer day)

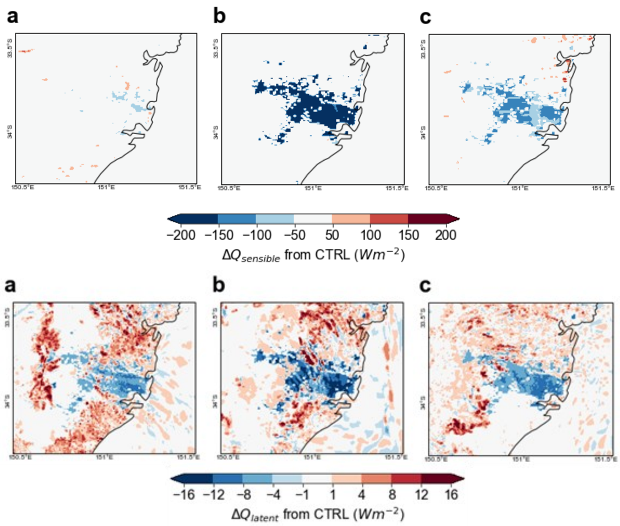


Not exact correspondence between surface temperature and air temperature drop.

Spatial distribution of the surface temperature and surface temperature drop in Sydney at 14:00 hrs, caused by the installation of the cool roofs, during a representative summer day.

UNSW SYDNEY

Results: Sensible and Latent Heat Fluxes



Variation in sensible and latent (panel below) heat flux at (a) 06:00 LT (b) 14:00 hrs LT, and (c) 18:00 LT, in Sydney, during a representative summer day when cool roofs are installed at city scale.

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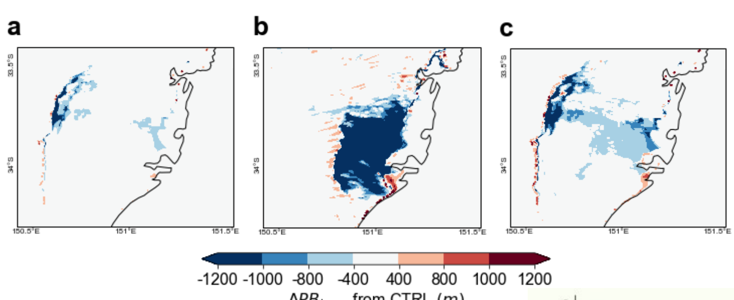
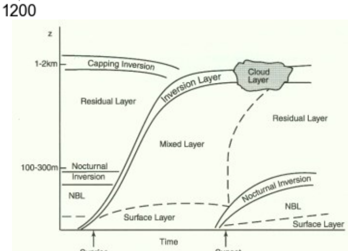
PBL reduction and wind speed reduction



- Lower surface temperatures caused by a large-scale deployment of cool roofs decrease the height of the planetary boundary layer (PBL).
- Increase in the albedo is expected to accelerate static stability at the diurnal scale of the PBL depth.
- Reduced PBL depth has potential penalties for air pollutant dilution and dispersion over the city domain
- Reduced cloud formation (due to reduced moisture transport) and increased cloud dissipation due to increased reflection are possible.



Stratification is not constant throughout the day (Stull, 1988)

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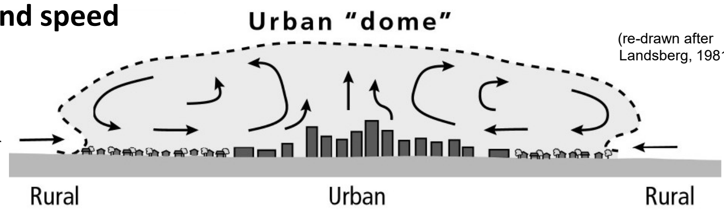
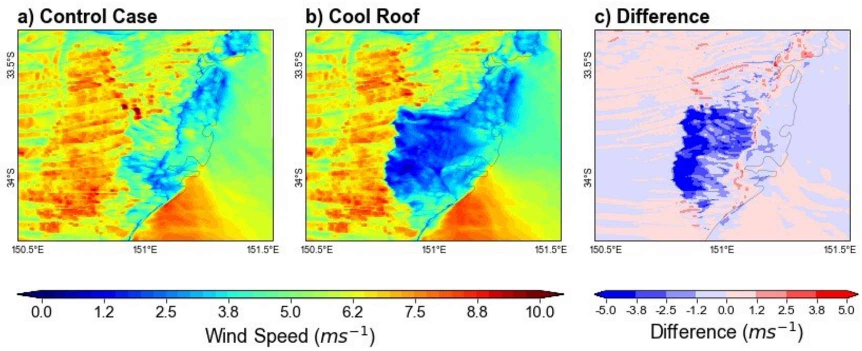
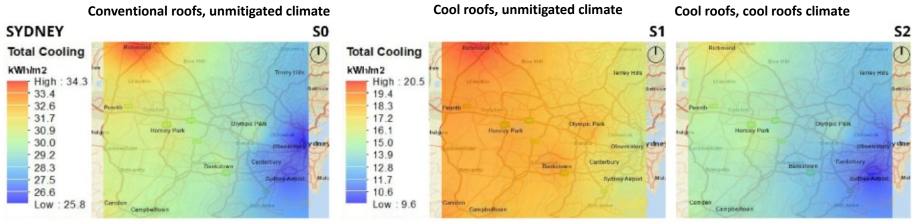
Results: Wind speed

Cool roofs lead to reduced wind circulation in the lower parts of the atmosphere and lower advection of warm winds from inland.



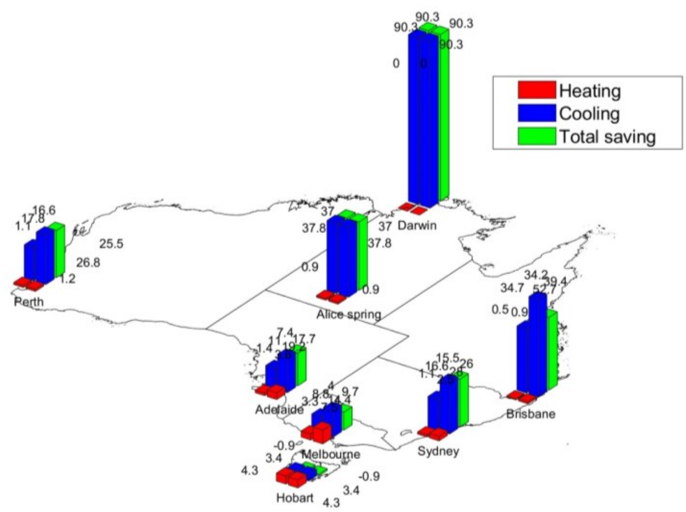


Uninsulated low-rise office building (Jan-Feb)



Mind the different scales

Cooling savings vs heating penalty



Jan-Feb | Office low vs high rise uninsulated/insulated

Building Type	City	Cooling load- Reference scenario	Cooling load reduction – cool roof unmitig. climate (S1)		Cooling load reduction – cool roof mitig. climate (S2)	
		kWh/m²	kWh/m²	%	kWh/m²	%
B01 | Low-rise office | no roof insulation | existing building	Sydney	25.8-34.3	10.2-13.8	37.6-42.0%	14.9-17.4	50.3-63.7%
	Melbourne	12.6-18.3	6.3-10	47.6-54.9%	8.3-11.7	59.3-65.7%
	Brisbane	43.6-46.3	11.3-15.6	25.6-33.7%	18.7-21.3	42.9-46.2%
	Adelaide	20.9-28.5	9.6-11.3	39.6-45.9%	12.5-13.9	47.7-59.8%
	Perth	21.7-32.3	10.3-13.0	40.4-47.7%	13.6-16.2	47.5-62.6%
B02 | High-rise office | no roof insulation |existing building	Sydney	19.3-25.5	1.9-2.8	9.2-11.1%	5.6-8.9	25.6-44.9%
	Melbourne	7.9-10.9	1.1-2.0	13-18.1%	3.0-4.0	32-40.9%
	Brisbane	34.2-35.2	2.0-3.0	5.7-8.8%	8.6-10.4	24.9-29.6%
	Adelaide	13.5-19.9	1.7-2.0	10.3-12.6%	4.5-5.0	22.8-37.4%
	Perth	13.2-22.1	1.8-2.3	10.5-13.6%	4.9-6.2	22.3-40.5%
B04 | High-rise office | w/ roof insulation |new building	Sydney	18.1-23.7	0.2-0.3	0.9-1.7%	3.7-7.3	19.9-39.2%
	Melbourne	7.1-9.7	0.1-0.2	1.3-1.9%	1.8-2.7	21.5-31.8%
	Brisbane	31.6-33.8	0.2-0.3	0.6-0.9%	6.3-8.5	19.9-25.4%
	Adelaide	12.2-18.4	0.2	1.2-1.3%	2.8-3.6	15.1-29.7%
	Perth	11.7-20.3	0.2	1.0-1.4%	2.9-4.4	14.3-32.5%

Indirect effects are substantial

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Jan-Feb | low vs high internal loads

Building Type	City	Cooling load-Reference scenario	Cooling load reduction – cool roof unmitig. climate (S1)		Cooling load reduction – cool roof mitig. climate (S2)	
		kWh/m²	kWh/m²	%	kWh/m²	%
B04 | High-rise office | w/ roof insulation |new building	Sydney	18.1-23.7	0.2-0.3	0.9-1.7%	3.7-7.3	19.9-39.2%
	Melbourne	7.1-9.7	0.1-0.2	1.3-1.9%	1.8-2.7	21.5-31.8%
	Brisbane	31.6-33.8	0.2-0.3	0.6-0.9%	6.3-8.5	19.9-25.4%
	Adelaide	12.2-18.4	0.2	1.2-1.3%	2.8-3.6	15.1-29.7%
	Perth	11.7-20.3	0.2	1.0-1.4%	2.9-4.4	14.3-32.5%
B07 | High-rise shopping mall | new building	Sydney	74.9-81.3	0.5-0.8	0.6-1%	9.9-17.1	13.2-21.8%
	Melbourne	39.6-45.3	0.4-0.6	1-1.4%	5.9-8.1	14.0-20.0%
	Brisbane	94.8-98.1	0.4-0.6	0.4-0.6%	14.4-18.4	15.0-18.8%
	Adelaide	54.2-64.0	0.5-0.6	0.8-0.9%	6.0-9.2	9.4-16.9%
	Perth	56.3-67.0	0.5	0.7-0.8%	7.3-10.2	10.9-18.1%

Even with high internal loads

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Jan-Feb | House, uninsulated vs insulated

Building Type	City	Cooling load-Reference scenario	Cooling load reduction – cool roof unmitig. climate (S1)		Cooling load reduction – cool roof mitig. climate (S2)	
		kWh/m²	kWh/m²	%	kWh/m²	%
B11 Stand-alone house-existing	Sydney	14.9-19.3	6.5-7.6	38.7-45.8%	9.2-10.7	53.9-69.9%
	Melbourne	6.6-10.0	3.4-7.5	51.9-75.3%	5.1-6.8	67.4-77.4%
	Brisbane	21.8-22.6	3.9-4.2	17.3-18.8%	8.6-10.1	38.8-44.9%
	Adelaide	11.8-15.8	5.7-6.0	38.1-48.1%	7.3-7.9	48.1-62.2%
	Perth	11.4-16.4	6.1-6.6	39.9-53.5%	7.7-8.7	50.3-67.9%
B17 | Stand-alone house-new building	Sydney	13-16.5	3.3-4	23.2-30.8%	6.1-8.5	42.2-62%
	Melbourne	4.6-7.1	2.1-3.0	37.5-46.9%	3.2-4.1	57.1-69.9%
	Brisbane	22.5-23.5	4.1-4.4	17.4-19.3%	8.8-10.4	39.1-44.6%
	Adelaide	9.0-12.3	2.9-3.3	23.7-33.9%	4.6-5.2	37.1-54.9%
	Perth	8.7-13.2	3.4-3.6	27.2-39.0%	5.2-5.9	40.8-60.3%

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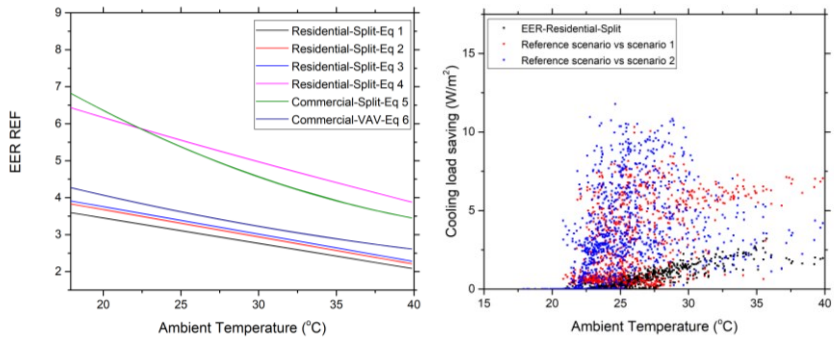
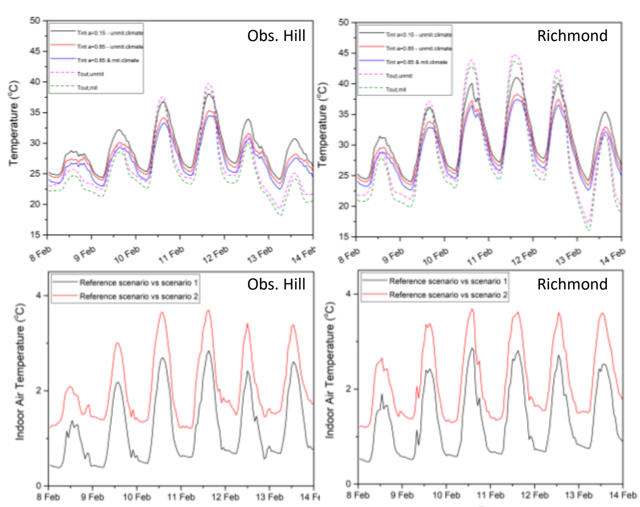
Cooling load savings by improved EER



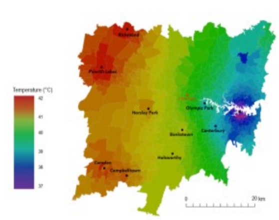
Cooling load savings by improved EER, Scenario 1 (building-scale application of cool roofs) (Scenario 1), and Scenario 2 (Combined building-scale and urban-scale application of cool roofs) as a function of ambient temperature in a new stand-alone house in Observatory station, Sydney (Climate zone 5-warm temperate).

EER as a function of the ambient temperature for cool roof scenario for six different AC systems .

Houses (new) |Free-floating indoor air temperature



Vital reduction in indoor air temperatures during heatwaves

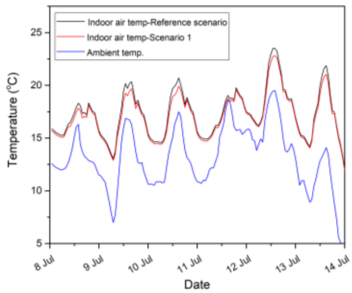


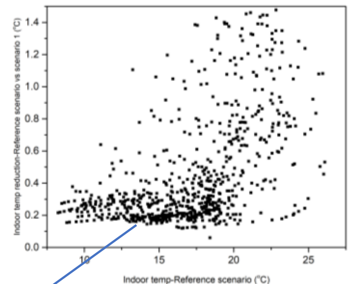
Temperature distribution at 3 pm in Feb 2017 (heatwave day)

House (new) | Indoor conditions - distribution

Summer. Number of hours with indoor air temperature above 26 °C in free-floating mode during a typical summer month

Station	Reference scenario	Cool roof unmit. climate	Cool roof & mitigated climate
Observatory Hill	422	339	253
Richmond	456	415	356

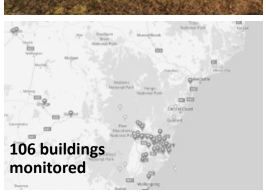


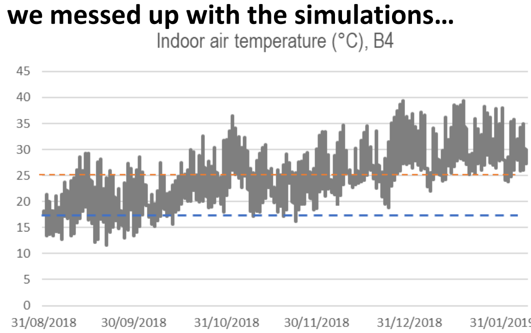


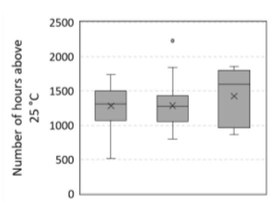
Cooling load savings: 25-38%
Heating penalty: 0.7-1.7%
Total thermal loads savings: 10-19%

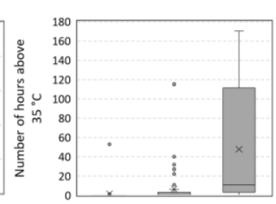
Limited impact on thermal balance

Discussion | If you think we messed up with the simulations…



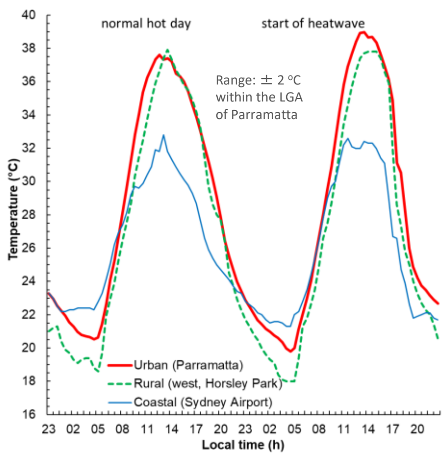




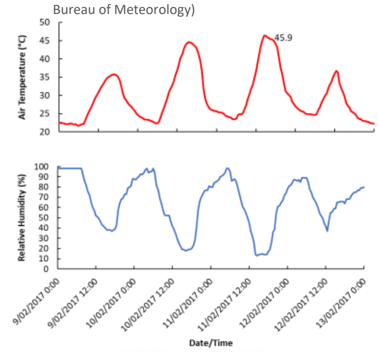


Haddad et al. (2022) https://doi.org/10.1016/j.enbuild.2022.112349
Project: Energy Efficiency in social housing (supported by OEH)

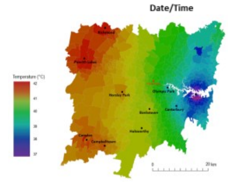
Discussion | Urban Heat mitigation and natural ventilation potential



Heatwave of February 2017. Data for Penrith (data from Bureau of Meteorology)



Air temperatures in the Greater Sydney (BoM) and in Parramatta LGA wards



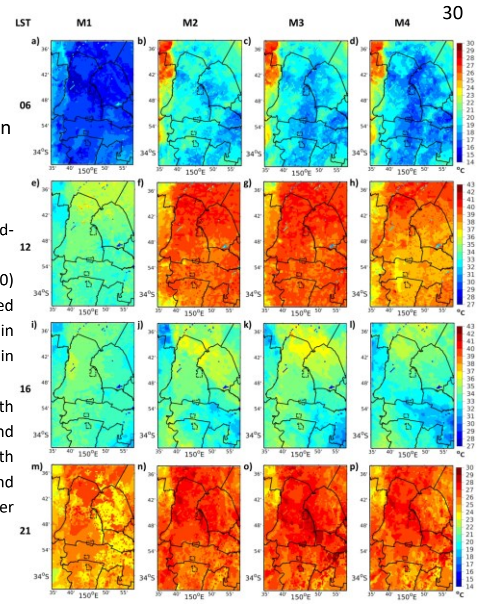
UNSW, Parramatta Urban Overheating Project (supported by City of Parramatta)

UNSW SYDNEY

Discussion | Natural ventilation potential in future climates

Present and future air temperature distribution in Western Sydney (South Creek)

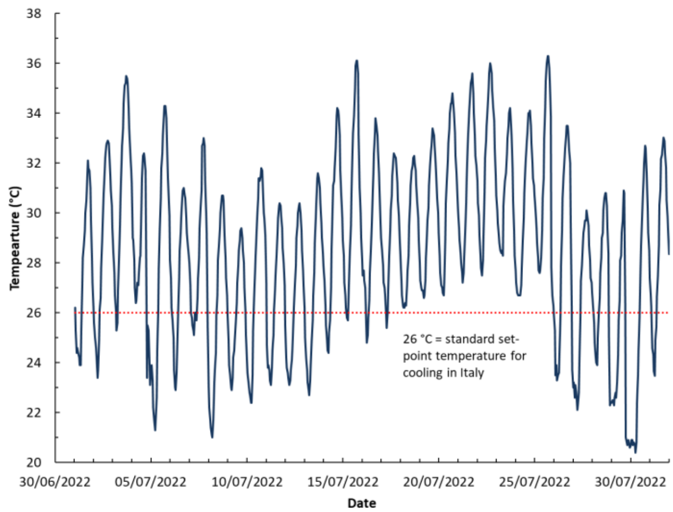
- Scenario M1. Present climate and land-use (2018).
- Scenario M2. future climate (2050) and current land-use (2018).
- Scenario M3. Future climate and future land use (2050) with increased built-up area (projections), increased anthropogenic heat flux, 670,000 non-irrigated trees in the inner domain and 3 million non-irrigated trees in the rest of Sydney.
- Scenario M4. Future climate and land use (2050) with mitigation: 2 million irrigated trees in the Parkland and 3 million irrigated trees in the rest of Sydney with increased albedo of urban impervious surfaces and landscape watering (3.5% of the catchment is water bodies).



Garshasbi et al. (2020)
https://doi.org/10.1016/j.solener.2020.04.089
UNSW, South Creek Urban Cooling Project (supported by iNSW)

UNSW SYDNEY

Discussion | Heatwaves in EU cities and night ventilation potential



Air temperature in Milan, Italy, in July 2022 (weather station at Politecnico di Milano)

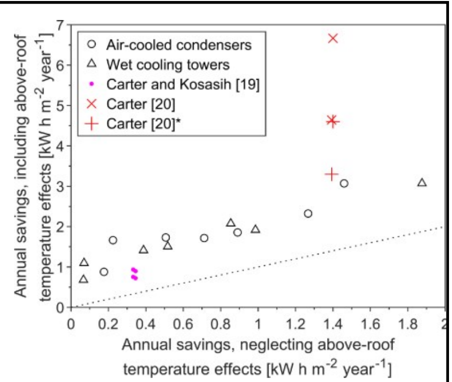
Data Courtesy Fondazione Meteo Milano Duomo.

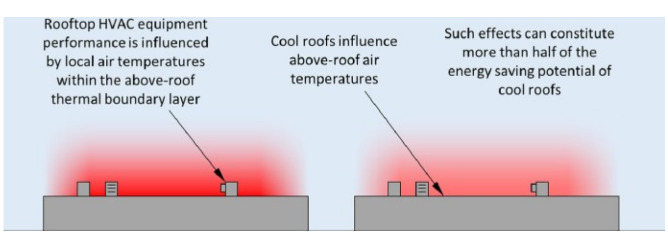
UNSW SYDNEY

Discussion | Large-scale cool roofs

Comparison of annual electricity savings per unit roof area, per 10 increase in roof solar reflectance index, calculated with and without taking above-roof temperature effects into account. Deviations between the data and the dotted line are due to above-roof temperature effects. Results identified by an asterisk in the legend have been modified to remove the effects of surface temperature augmentation.

CRC project RP1037 - Driving Increased Utilisation of Cool Roofs on Large Footprint Buildings



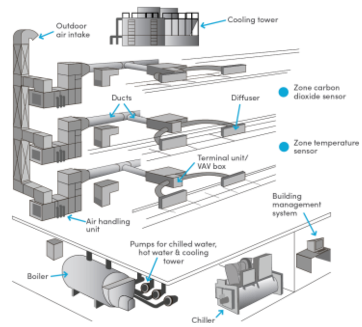


Green et al. (2020)
https://doi.org/10.1016/j.enbuild.2020.110071

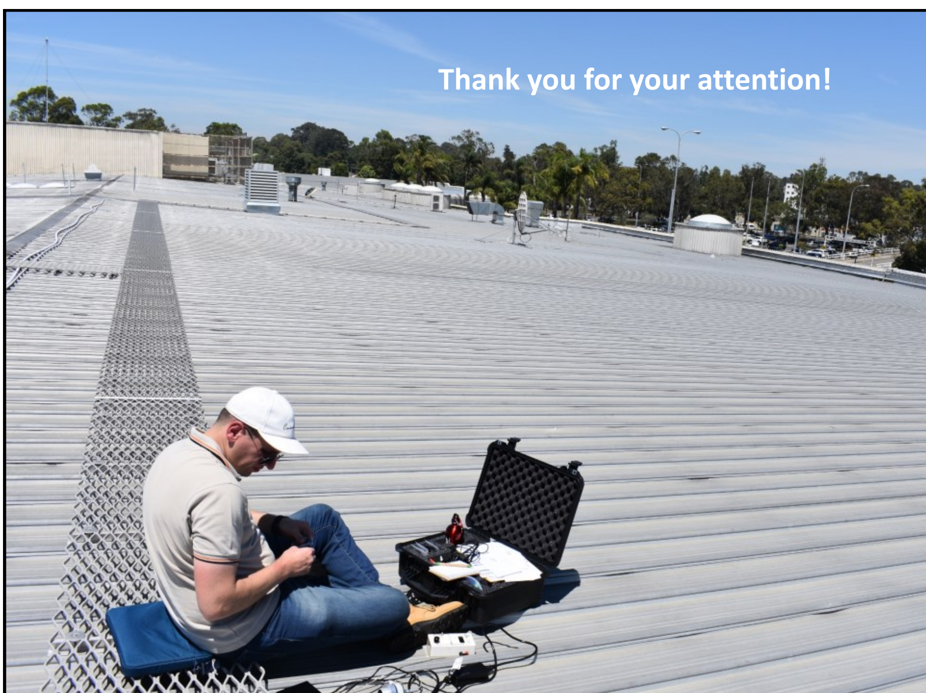
UNSW SYDNEY

Summary of main influence of cool materials on ventilation

- Lower penetration of warm winds from inland in coastal cities such as Sydney
- Increased natural ventilation potential (lower outdoor temperatures)
- Lower air intake temperatures (for air handling units and make-up air) and higher effective EER
- Indirect effects are substantial even for highly insulated and high-rise buildings
- Lower peak indoor air temperatures in houses by more than 4 °C during heatwaves

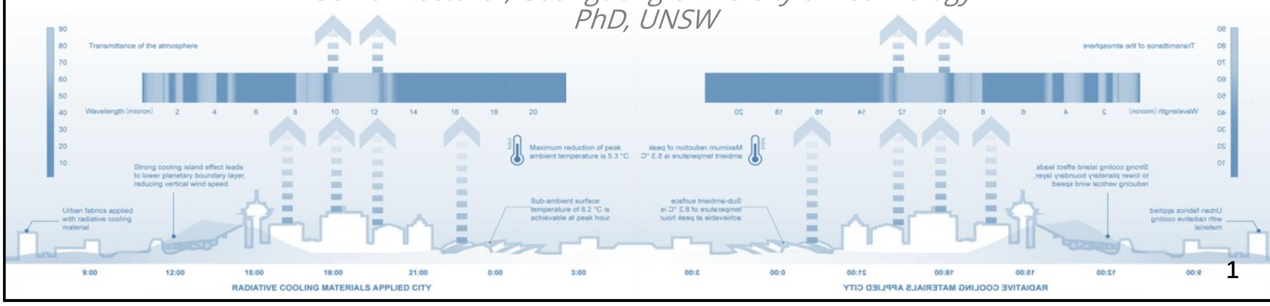


UNSW SYDNEY



Recent Developments of Super Cool Materials

Dr Jie Feng
Senior Lecturer, Guangdong University of Technology
PhD, UNSW



1

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Outline

1 Fundamentals and performance

- Basics
- Performance and limitations
- Commercialization
- Impact

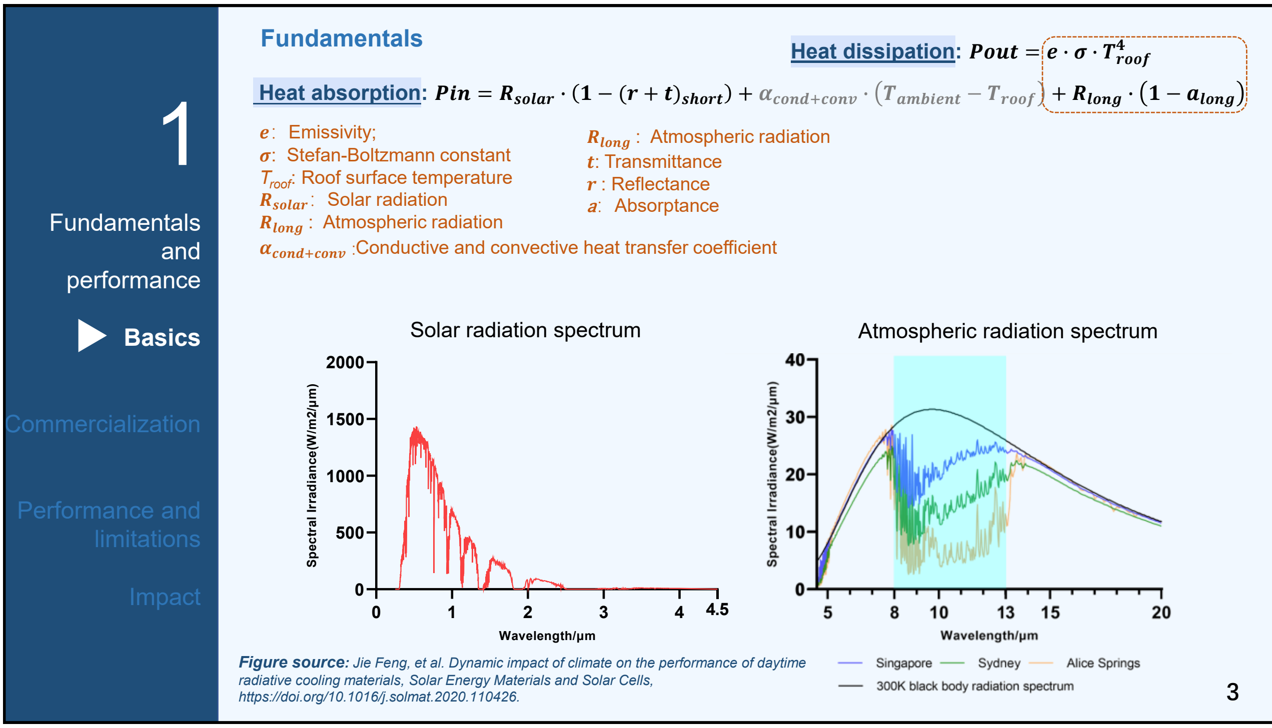
2 Further increase the cooling performance

- Integration of fluorescent pigment
- Prevention of pigment aggregation
- Porous morphology

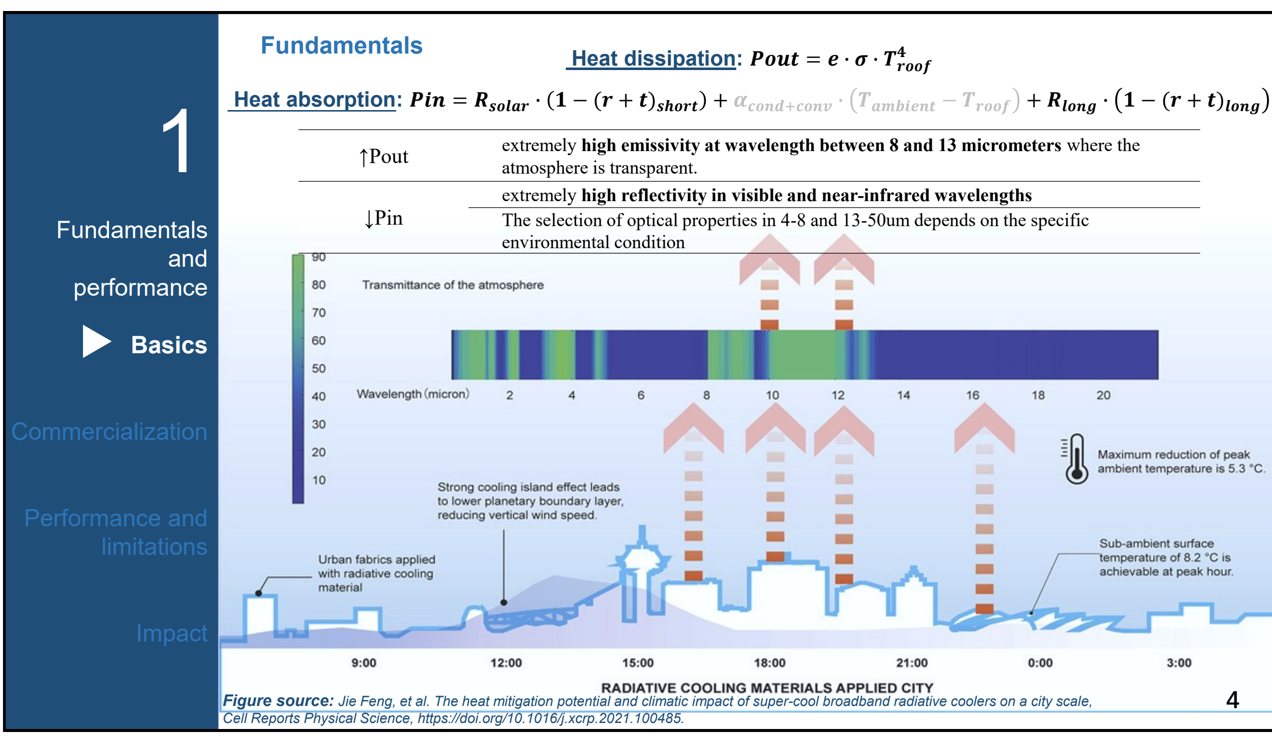
3 Summary and outlook

2

2


1
Fundamentals and performance
Basics
Commercialization
Performance and limitations
Impact
Fundamentals
Heat dissipation: $Pout = e \cdot \sigma \cdot T_{roof}^4$
Heat absorption: $Pin = R_{solar} \cdot (1-(r+t)_{short}) + \alpha_{cond+conv} \cdot (T_{ambient} - T_{roof}) + R_{long} \cdot (1-a_{long})$
e: Emissivity;
σ: Stefan-Boltzmann constant
T_{roof}: Roof surface temperature
R_{solar}: Solar radiation
R_{long}: Atmospheric radiation
$\alpha_{cond+conv}$:Conductive and convective heat transfer coefficient
R_{long}: Atmospheric radiation
t: Transmittance
r : Reflectance
a: Absorptance
Solar radiation spectrum
Spectral Irradiance(W/m2/μm)
2000
1500
1000
500
0
0
1
2
3
4
4.5
Wavelength/μm
Atmospheric radiation spectrum
Spectral Irradiance(W/m2/μm)
40
30
20
10
0
5
8
10
13
15
20
Wavelength/μm
Singapore
Sydney
Alice Springs
300K black body radiation spectrum
Figure source: Jie Feng, et al. Dynamic impact of climate on the performance of daytime radiative cooling materials, Solar Energy Materials and Solar Cells, https://doi.org/10.1016/j.solmat.2020.110426.
3

3


1
Fundamentals and performance
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Fundamentals
Heat dissipation: $Pout = e \cdot \sigma \cdot T_{roof}^4$
Heat absorption: $Pin = R_{solar} \cdot (1-(r+t)_{short}) + \alpha_{cond+conv} \cdot (T_{ambient} - T_{roof}) + R_{long} \cdot (1-(r+t)_{long})$
↑Pout
extremely high emissivity at wavelength between 8 and 13 micrometers where the atmosphere is transparent.
↓Pin
extremely high reflectivity in visible and near-infrared wavelengths
The selection of optical properties in 4-8 and 13-50um depends on the specific environmental condition
90
80
70
60
50
40
30
20
10
Transmittance of the atmosphere
Wavelength (micron)
2
4
6
8
10
12
14
16
18
20
Maximum reduction of peak ambient temperature is 5.3 °C.
Strong cooling island effect leads to lower planetary boundary layer, reducing vertical wind speed.
Urban fabrics applied with radiative cooling material
Sub-ambient surface temperature of 8.2 °C is achievable at peak hour.
9:00
12:00
15:00
18:00
21:00
0:00
3:00
RADIATIVE COOLING MATERIALS APPLIED CITY
Figure source: Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.
4

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1

Fundamentals and performance

▶ **Basics**

Performance and limitations

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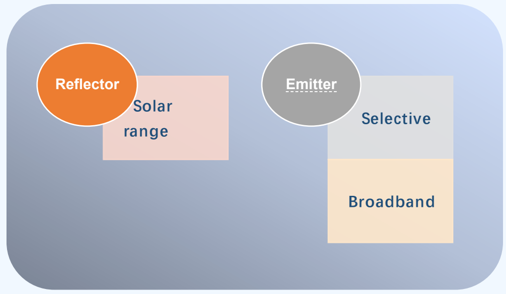
Ideal cooler



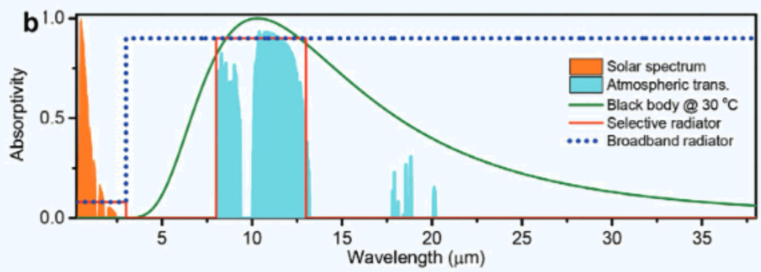


Figure source: *Yang, Y., & Zhang, Y. (2020). Passive daytime radiative cooling: Principle, application, and economic analysis. MRS Energy & Sustainability, 7, E18. doi:10.1557/mre.2020.18*

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Fundamentals and performance

Basics

▼ **Performance and limitations**

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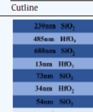
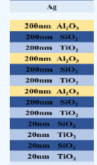
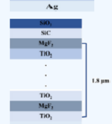
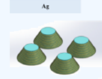
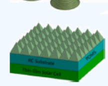
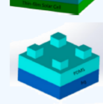
Performance-Photonic crystal

One-dimensional photonic crystal requires electron beam evaporation

Multi-dimensional photonic crystal requires photolithography

Optical properties and cooling effect of multi-layer photonic radiative cooling structures.

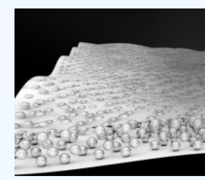
Year	Cooling structure: Cutline	Cooling structure: Description	Optical properties	$\Delta T = T_a - T_r$ (°C)	$P_{net\text{-}cooling}$ (W/m²)
2014		Seven layers of alternating HfO_2 and SiO_2(Raman et al., 2014)	R_{solar} = 0.97 ε_{LWIR} = 0.5–0.8	5	40
2017		Combination of SiO_2, TiO_2 and Al_2O_3 layers (Kecebas et al., 2017)	R_{solar} = 0.94 ε_{LWIR} = 0.84	N.A.	100
2013		3 groups of 5 layers of MgF_2 and TiO_2 on a silver substrate, 2 laminated SiC and quartz (Rephaeli et al., 2013)	R_{solar} = 0.965 ε_{LWIR} = 0.1–0.95	N.A.	105
2015		Symmetric conical meta-materials composed of alternating layers of Al and Ge (Hossain et al., 2015)	R_{solar} = 0.97 ε_{LWIR} = 0.99	9	N.A.
2019		The upper surface of PDMS is a pyramid structure (Lee & Luo, 2019)	R_{solar} = 0.95 ε_{LWIR} = 0.98	6.2	20
2020		PDMS films with 2D grating patterns (Song et al., 2020)	ε_{LWIR} = 0.99	N.A.	N.A.

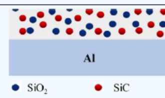
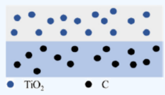
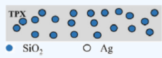
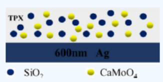
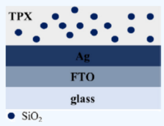
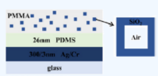
Info source: *Yan Cui, et al. Progress of passive daytime radiative cooling technologies towards commercial applications, Particuology, Volume 67,2022,Pages 57-67,https://doi.org/10.1016/j.partic.2021.10.004.*

6

Performance-film or coatings including random particles



Year	Cooling structure: Cutline	Cooling structure: Description	Optical properties	$\Delta T = T_a - T_r$ (°C)	$P_{net\text{-}cooling}$ (W/m²)
2010		25 µm thick SiC and transparent PE coating containing SiO_2 nanopartcles (Gentle & Smith, 2010)	$R_{solar} = 0.9$, $\varepsilon_{LWIR} = 0.35–0.95$	12–25	N.A.
2016		Acrylic resin randomly doped with TiO_2 and carbon black particles (Huang & Ruan, 2017)	$R_{solar} = 0.9$, $\varepsilon_{LWIR} > 0.9$	6	100
2017		Silvered glass beads were randomly embedded in the polymer matrix (Yao Zhai et al., 2017)	$R_{solar} = 0.96$, $\varepsilon_{LWIR} = 0.93$	8	93
2019		TPX film doped with nano-sized SiO_2 and $CaMoO_4$ particles (Liu, Bai et al., 2019)	$R_{solar} = 0.94$, $\varepsilon_{LWIR} = 0.85$	N.A.	47
2019		Nanoporous SiO_2 microspheres-polymethylpentene (TPX) (Yang, Gao et al., 2020)	$\varepsilon_{LWIR} = 0.91$	4.5	N.A.
2020		SiO_2 nanoshell (Suichi et al., 2020)	$R_{solar} = 0.98$	2.3	N.A.

Info source: *Yan Cui, et al. Progress of passive daytime radiative cooling technologies towards commercial applications, Particuology, Volume 67,2022,Pages 57-67,https://doi.org/10.1016/j.partic.2021.10.004.*

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Fundamentals and performance

Basics

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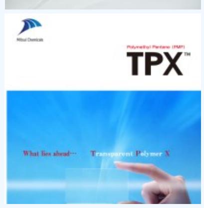
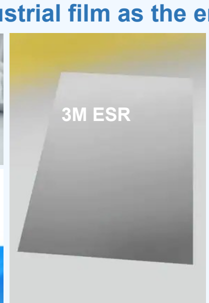
Performance-industrial film as the emitter





Polyvinyl fluoride (PVF) film
C-H and C-F bonds

Polymethylpentene (TPX)
C-H bond

Polytetrafluoroethylene (PTFE or Teflon)
C-F bond

Acrylic
C-O and C-H bonds

poly(methyl methacrylate) (PMMA)
C-H, and C-O bonds

Polyvinylidene fluoride (PVDF) **C-H and C-F bonds**

Solar Energy, Vol. 17, pp. 83–89. Pergamon Press 1975. Printed in Great Britain

1975

THE RADIATIVE COOLING OF SELECTIVE SURFACES

S. CATALANOTTI, V. CUOMO, G. PIRO, D. RUGGI, V. SILVESTRINI and G. TROISE
Istituto di Fisica Sperimentale dell'Università di Napoli, Via Antonio Tari 3, 80138 Napoli, Italy

(Received 22 March 1974; in revised form 26 August 1974)

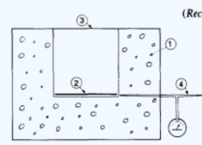


Fig. 4. Schematic drawing of the experimental set-up. 1. Insulating material; 2. Selective radiator; 3. Transparent cover; 4. Thermocouple.

The radiator
The selective radiator has been built by coating a sheet of evaporated aluminum with a thin film (12·5 µm) of TEDLAR, a polyvinyl-fluoride plastic produced by Du Pont de Nemours.

Vibration region	Functional groups	Dominant Group
X – H stretching region (4000-2500 cm⁻¹)	C – H, O – H, N – H	N – H
Triple bond region (2500—2000 cm⁻¹)	C ≡ N, C ≡ C	C ≡ N
Double bond region (2000-1500 cm-1)	C = C, C = O, C = N	C = O
Finger-print region (crowded region, mainly bending vibration) (1500-600 cm-1)	C – H, C – O, C – N, C – Cl, C – F	Weak but significant overlapping
Skeletal vibration region (600-400+cm⁻¹)	Heavy atoms and molecules	

Info source: *Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.*
A. Aili, Z.Y. Wei, Y.Z. Chen, D.L. Zhao, R.G. Yang, X.B. Yin, Selection of polymers with functional groups for daytime radiative cooling, Materials Today Physics, https://doi.org/10.1016/j.mtphys.2019.100127.

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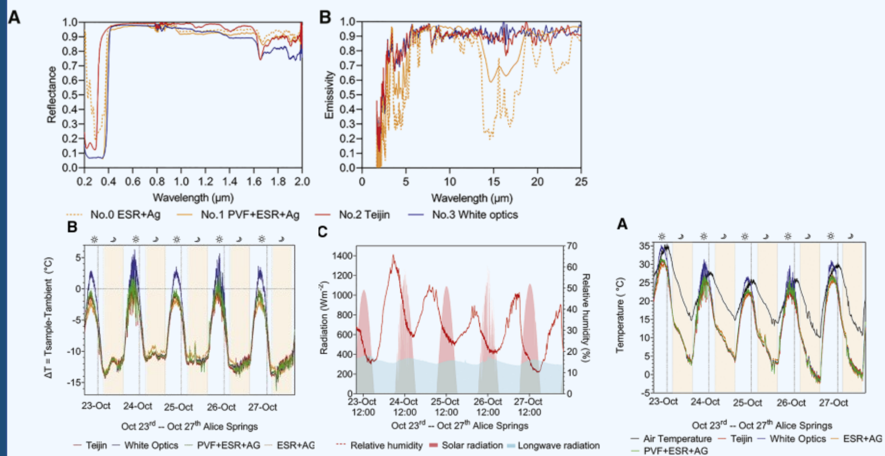
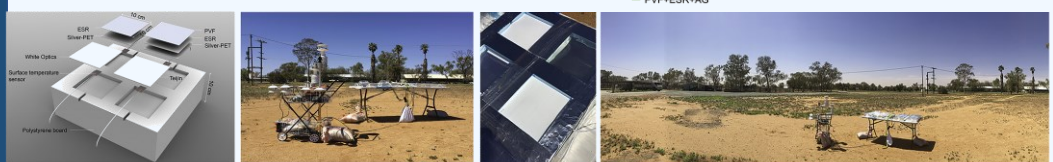
Performance-industrial film





Info source: *Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.*

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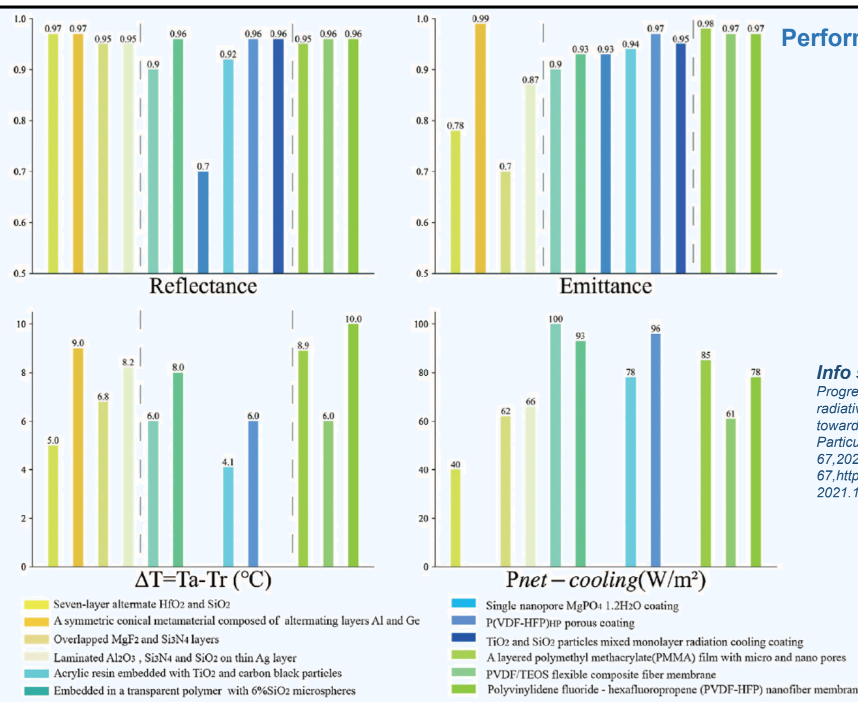
Performance summary



Info source: *Yan Cui, et al. Progress of passive daytime radiative cooling technologies towards commercial applications, Particuology, Volume 67,2022,Pages 57-67,https://doi.org/10.1016/j.partic.2021.10.004.*

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Limitations-Humid climate

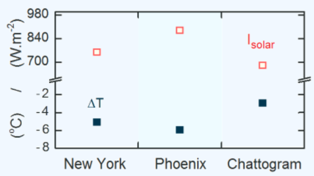
Locations and Weather

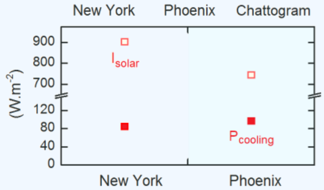
Phoenix (Midlatitude, Arid)
Elevation 349 m, Date: 2018-03-03, Sky clear, Air temperature ~26.5° C, TPW ~8mm

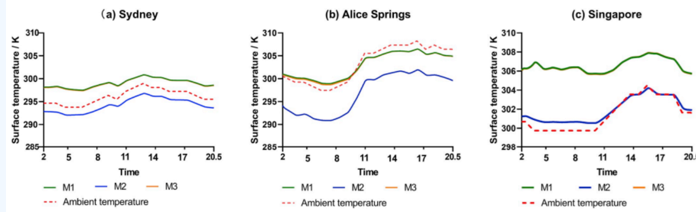
New York (Midlatitude, Coastal)
Elevation 85 m, Date: 2018-03-31, Sky clear, Air temperature ~14.5° C, TPW ~6 mm

Chattogram (Tropical, Coastal)
Elevation 56 m, Date: 2018-01-10, Fog/Haze, Air temperature ~24° C, TPW ~10 mm

*TPW = Total Precipitable water







Info source:

Jie Feng, et al. Dynamic impact of climate on the performance of daytime radiative cooling materials, Solar Energy Materials and Solar Cells, https://doi.org/10.1016/j.solmat.2020.110426

J Mandal el al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science. DOI: 10.1126/science.aat9513

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Impact

Limitations-Humid climate

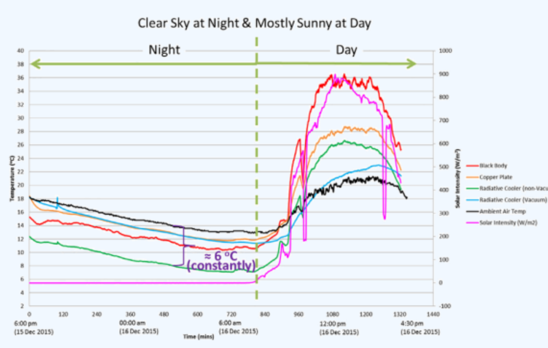
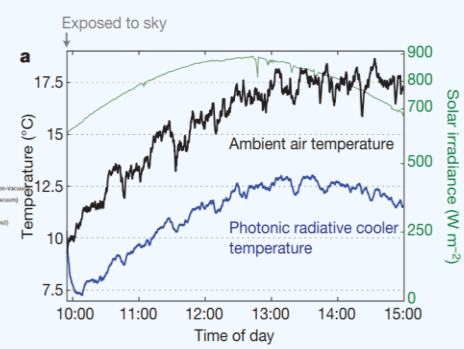
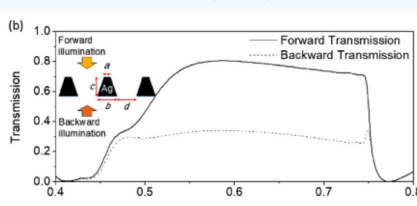


Fig. 10. Temperature profile of the passive radiative coolers under a clear night sky weather condition.

Hong Kong



Same material & settings
Stanford, California



C.Y. Tso, K.C. Chan, Christopher Y.H. Chao, A field investigation of passive radiative cooling under Hong Kong's climate, Renewable Energy, https://doi.org/10.1016/j.renene.2017.01.018.

Wong, R. Y. M., Tso, C. Y., Chao, C. Y. H., Huang, B., & Wan, M. P. (2018). Ultra-broadband asymmetric transmission metallic gratings for subtropical passive daytime radiative cooling. Solar Energy Materials and Solar Cells, 186, 330-339. https://doi.org/10.1016/j.solmat.2018.07.002

Possible solution: asymmetric transmission metallic gratings

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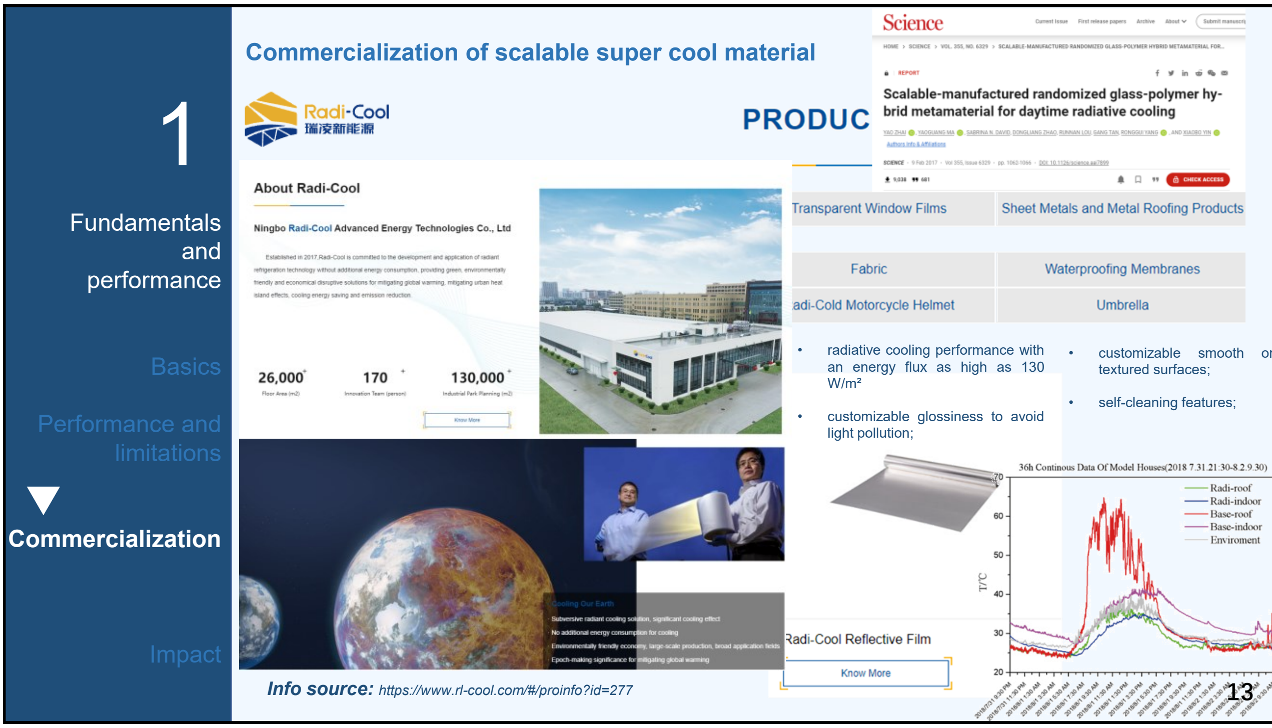
1
Fundamentals and performance
Basics
Performance and limitations
Commercialization
Impact
Commercialization of scalable super cool material
Radi-Cool
瑞凌新能源
PRODUC
Science
Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling
About Radi-Cool
Ningbo Radi-Cool Advanced Energy Technologies Co., Ltd
26,000
170
130,000
Know More
Cooling Our Earth
Subversive radiant cooling solution, significant cooling effect
No additional energy consumption for cooling
Environmentally friendly economy, large-scale production, broad application fields
Epoch-making significance for mitigating global warming
Transparent Window Films
Sheet Metals and Metal Roofing Products
Fabric
Waterproofing Membranes
adi-Cold Motorcycle Helmet
Umbrella
• radiative cooling performance with an energy flux as high as 130 W/m²
• customizable glossiness to avoid light pollution;
• customizable smooth or textured surfaces;
• self-cleaning features;
Radi-Cool Reflective Film
Know More
36h Continous Data Of Model Houses(2018 7.31 21:30-8.2 9.30)
Radi-roof
Radi-indoor
Base-roof
Base-indoor
Enviroment
T/C
70
60
50
40
30
20
Info source: https://www.rl-cool.com/#/proinfo?id=277
13

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1
Fundamentals and performance
Basics
Performance and limitations
Commercialization
Impact
Commercialization of scalable super cool material
Radi-Cool
瑞凌新能源
Big and High Public Buildings
Industrial Plant
Industrial standard plant, plant construction, etc
Transportation
Large and small passenger cars, cars, new energy vehicles, logistics vehicles, etc
Electronic/electrical Equipment
Outdoor Goods
High-end Agriculture and Animal Husbandry
Petrochemical Engineering
Solar Photovoltaic
Info source: https://www.rl-cool.com/#/proinfo?id=277
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Fundamentals and performance

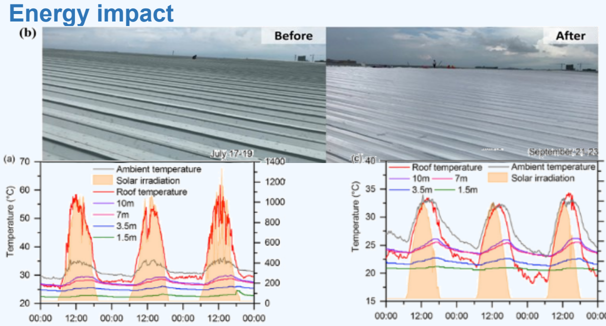
Basics

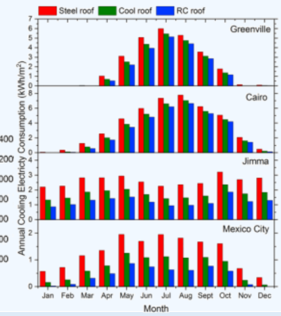
Performance and limitations

Commercialization

Impact

Energy impact





Info source: *Ningsheng Wang, Yinyan Lv, Dongliang Zhao, Wenbo Zhao, Jingtao Xu, Ronggui Yang, Performance evaluation of radiative cooling for commercial-scale warehouse, Materials Today Energy, https://doi.org/10.1016/j.mtener.2021.100927.*

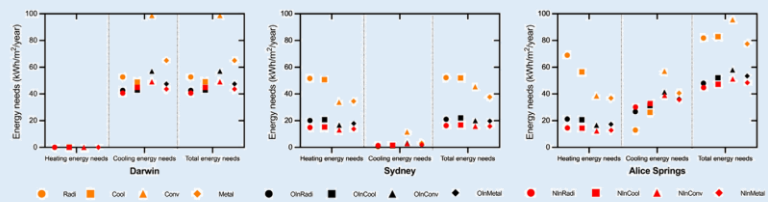


Fig. 8. The annual heating and cooling energy needs for the buildings with different insulation conditions applied with the four roof materials in a) Darwin b) Sydney and c) Alice Springs.

Findings: radiative cooling roof can reduce more the annual energy use in a cooling-dominated climate. With insulation added, the difference in cooling, heating, or total energy needs in buildings with different roof types has been largely decreased. But under cooling dominated climate or climate with mixed heating and cooling, the radiative cooling material still has advantages in reducing the overall energy consumption in buildings.

Info source: *Jie Feng, Maria Saliari, Kai Gao, Mattheos Santamouris, On the cooling energy conservation potential of super cool roofs, Energy and Buildings, https://doi.org/10.1016/j.enbuild.2022.112076.*

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Fundamentals and performance

Basics

Performance and limitations

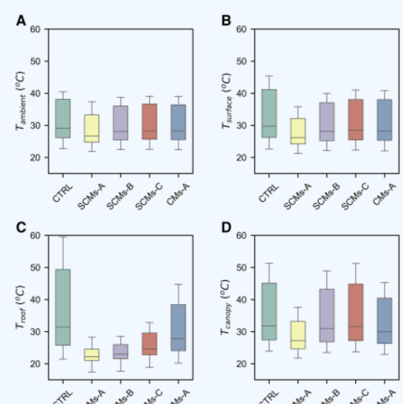
Commercialization

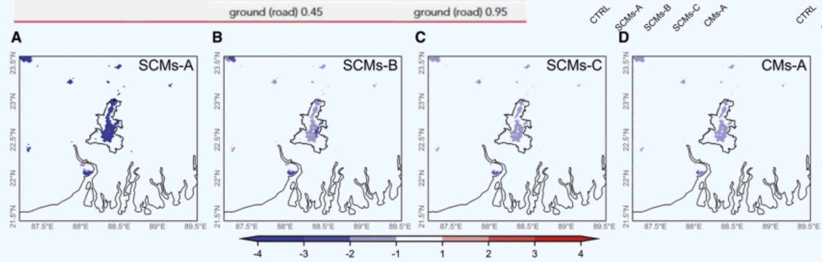
Impact

Large scale impact

Table 1. Design of numerical simulation for SCMs

Numerical simulations	Type of roof	Modification of WRF-SLUM in a high-density residential area: Albedo (high-density residential)	Emissivity
Control case (CTRL)	conventional	roof 0.20 wall 0.20 ground (road) 0.20	roof 0.90 wall 0.90 ground (road) 0.95
Implementing case			
SCM-A	super-cool	roof 0.96 wall 0.91 ground (road) 0.71	0.97 for all
SCM-B	super-cool	roof 0.96 wall 0.30 ground (road) 0.40	0.97 for all
SCM-C	super-cool	roof 0.90 wall 0.20 ground (road) 0.20	0.90 for all
Comparison case			
CM-A	cool	roof 0.65 wall 0.60 ground (road) 0.45	roof 0.90 wall 0.90 ground (road) 0.95





Info source: *Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.*

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2

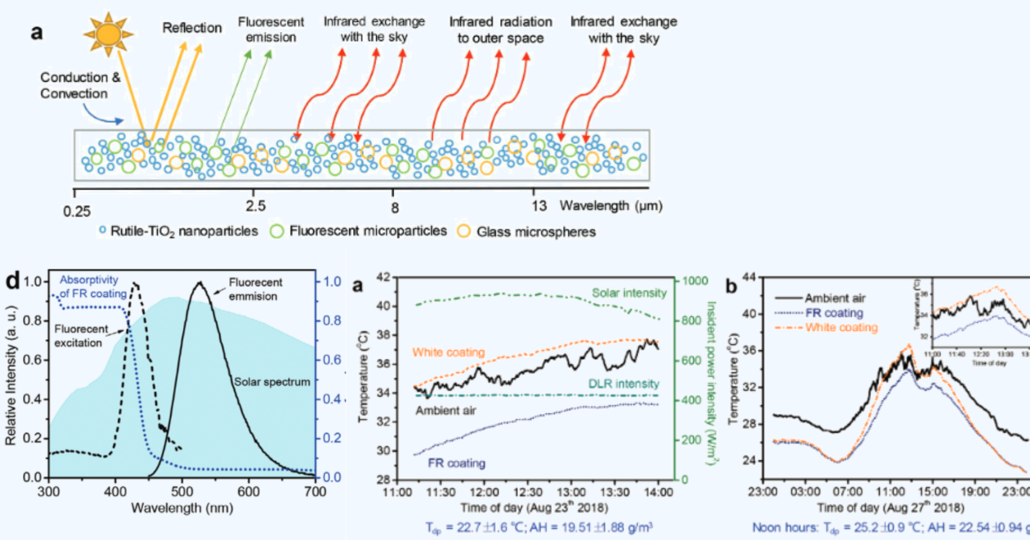
Further increase the cooling performance

▶ **Integration of fluorescent pigment**

Prevention of pigment aggregation

Porous morphology

Integration of fluorescent pigment



Info source: *Xue, X., Qiu, M., Li, Y., Zhang, Q. M., Li, S., Yang, Z., Feng, C., Zhang, W., Dai, J.-G., Lei, D., Jin, W., Xu, L., Zhang, T., Qin, J., Wang, H., Fan, S., Creating an Eco-Friendly Building Coating with Smart Subambient Radiative Cooling. Adv. Mater. 2020, 32, 1906751. https://doi.org/10.1002/adma.201906751*

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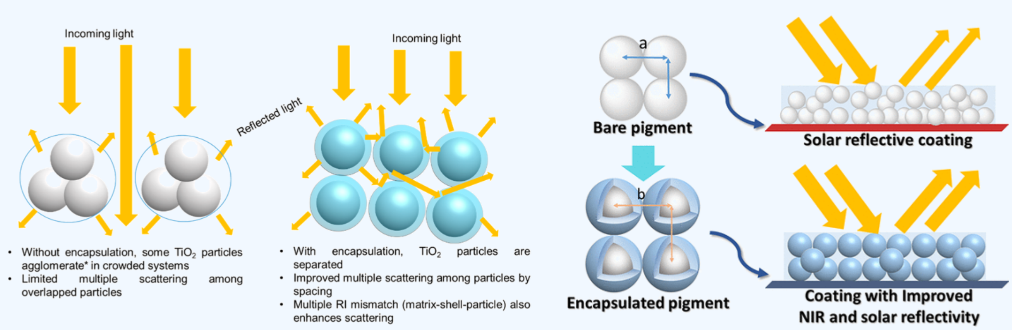
Further increase the cooling performance

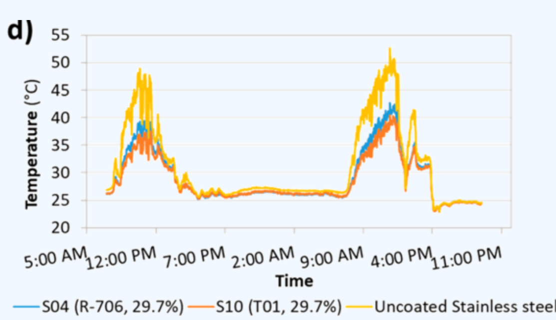
Integration of fluorescent pigment

▶ **Prevention of pigment aggregation**

Porous morphology

Prevention of pigment aggregation





Info source: *Polymer-Encapsulated TiO2 for the Improvement of NIR Reflectance and Total Solar Reflectance of Cool Coatings*
Siming Dong, Jing Yang Quek, Alexander M. Van Herk, and Satyasankar Jana
Industrial & Engineering Chemistry Research 2020 59 (40), 17901-17910
DOI: 10.1021/acs.iecr.0c03412

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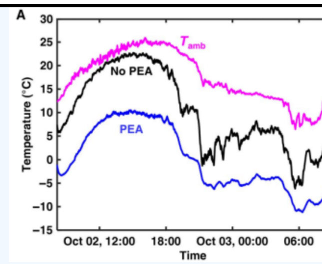
Further increase the cooling performance

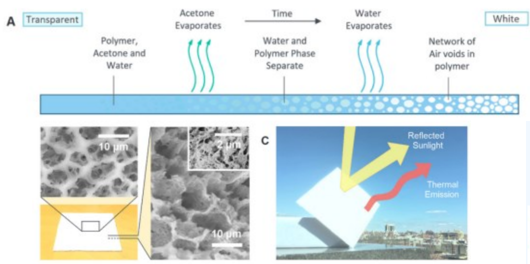
Integration of fluorescent pigment

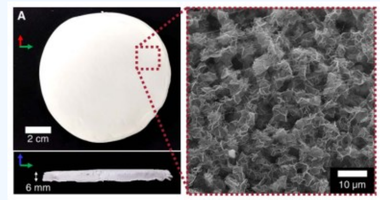
Prevention of pigment aggregation

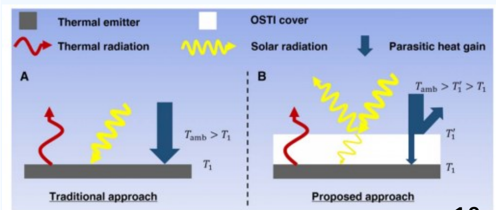
▶ **Porous morphology**

Porous morphology results in high solar reflectance









Info source:

J Mandal el al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science. doi: 10.1126/science.aat9513

A. Leroy et al. High-performance subambient radiative cooling enabled by optically selective and thermally insulating polyethylene aerogel. Science. doi: 10.1126/sciadv.aat9480

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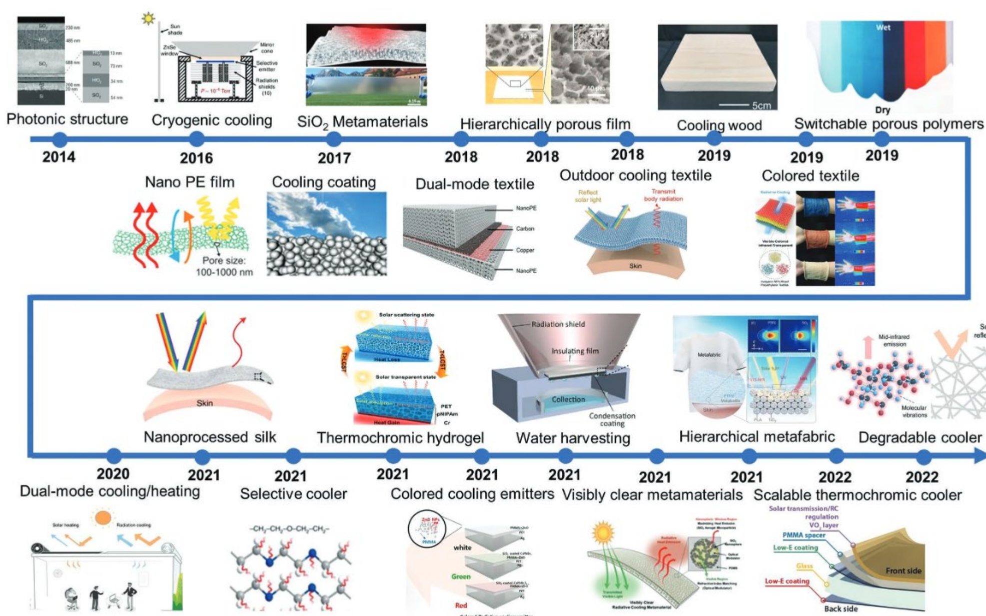
Summary and outlook

- Cooling Performance
- Mechanical Performance
- Weather Fastness
- Aesthetics
- Special Functions

Summary



Info source: *Liu, J., Tang, H., Jiang, C., Wu, S., Ye, L., Zhao, D., Zhou, Z., Micro-Nano Porous Structure for Efficient Daytime Radiative Sky Cooling. Adv. Funct. Mater. 2022, 32, 2206962. https://doi.org/10.1002/adfm.202206962*

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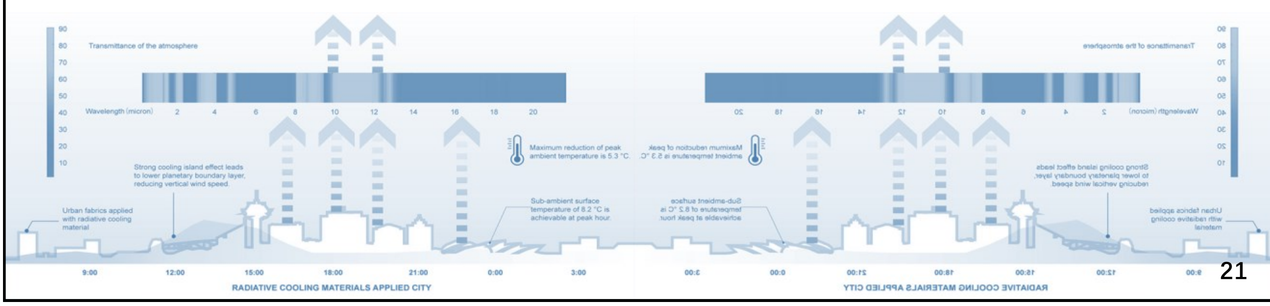
Thanks for your attention



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Fluorescent-based Cool Materials- Recent Developments

Samira Garshasbi

PhD, High performance architecture, UNSW
ESD Consultant, Arup

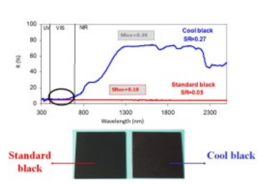
Different generations of cool materials

First Generation	Second Generation	Third Generation
Light-coloured cool materials	NIR-reflective cool materials	Fluorescent-based cool materials (Bulk & Nano-scale)

First Generation

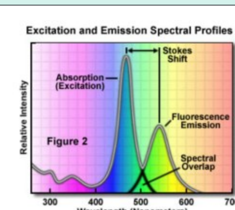
- Glare & aesthetic
- Limited application for roofs of high-rise buildings

Second Generation



- Limited cooling potential
- Reflection only in NIR-range

Third Generation



- Preserve colour
- Re-emission in visible range.
- Possibility for the integration of nano-scale fluorescent materials with NIR-reflective materials.

Fluorescent Cooling

Fluorescent Cooling/photoluminescence (PL) effect:
Fluorescent cooling refers to radiative/non-thermal relaxation of the absorbed light.

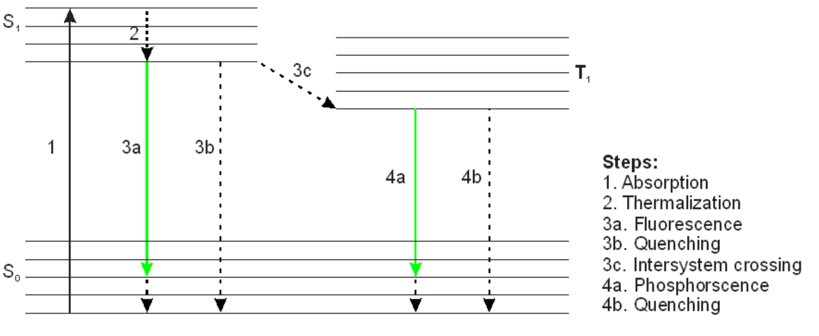
Fluorescent materials categorization:

1. Conventional bulk fluorescent materials (e.g. ruby) with fixed fluorescent properties and limited/certain heat-rejection potential.

2. Nano-scale fluorescent materials (e.g. Quantum Dots (QDs-Nano-scale semiconductor materials) (Tuneable fluorescent properties & possibility for integration with NIR-reflective materials).

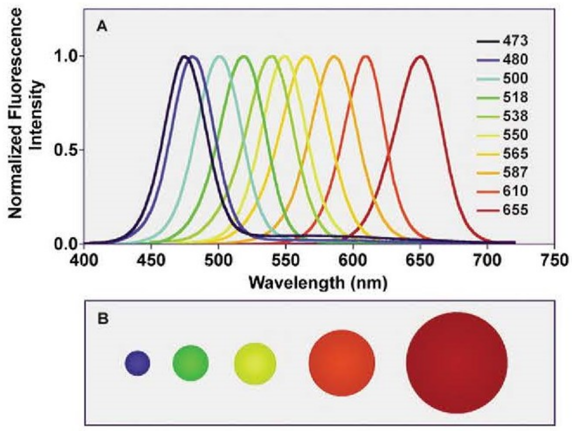
Quantum Dots

Fluorescent effect refers to the radiative/non-thermal relaxation of excited electrons. The fluorescent cooling effect occurs for the incident light having an energy level equal or higher than the QDs bandgap energy.



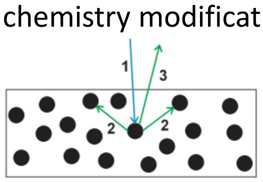
Fluorescent Cooling

❖ Absorption edge wavelength:
The wavelength with an energy level of bandgap energy is known as absorption edge wavelength (λ_{AE}).

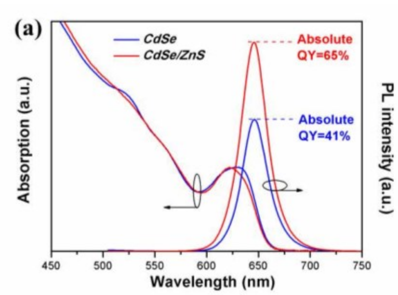


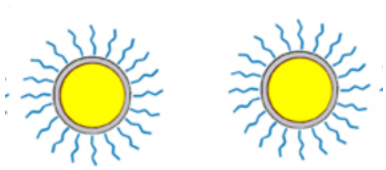
Quantum Dots

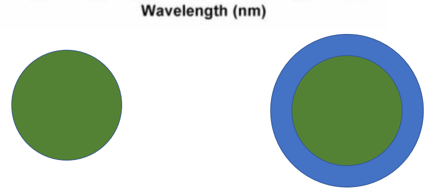
❖ Quantum yield, defined by the number of reemitted photons divided by the number of absorbed photons, could be adjusted by modifying the interparticle distance and surface chemistry modifications.



Interaction of light with QDs nanoparticles: (1) Light enters from the top surface and is absorbed by the QDs nanoparticles, (2) Light is reabsorbed by another QDs nanoparticle, (3) Light reemitted from the top surface.





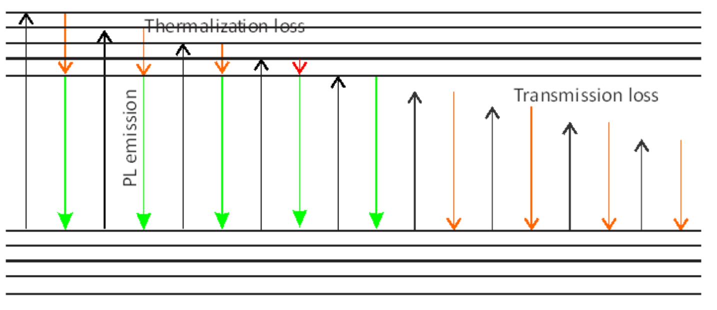


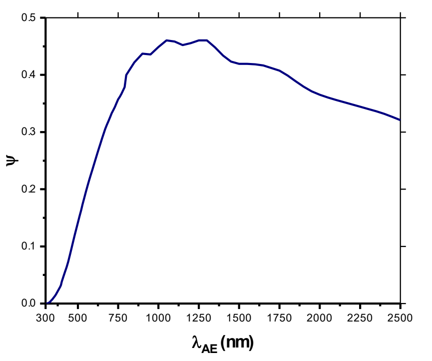
Core Quantum Dots Core-Shell Quantum Dots

Quantum Dots

Cooling potential theoretical limit

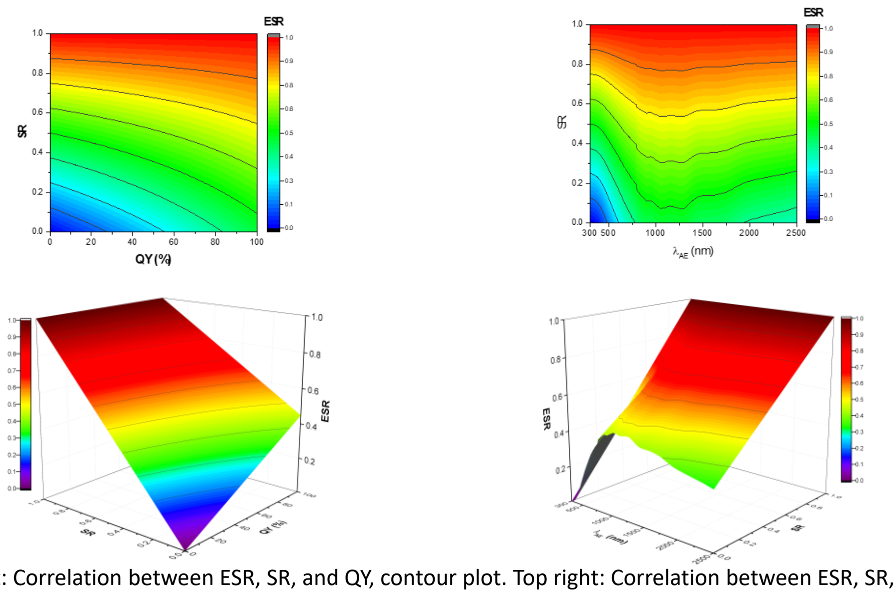
The fluorescent cooling theoretical limit is 0.15, 0.21, 0.23, 0.27, 0.43 for blue-emitting, green-emitting, yellow-emitting, orange-emitting, and red-emitting fluorescent materials, respectively.





Correlation between ψ and λ_{AE} for conventional Stokes-shift fluorescent materials

Optimization: Re-emitted energy through photoluminescence(PL) effect



Top left: Correlation between ESR, SR, and QY, contour plot. Top right: Correlation between ESR, SR, and λAE, contour plot. Bottom left: Correlation between ESR, SR, and QY, 3D plot. Bottom right: Correlation between ESR, SR, and λAE, 3D plot.

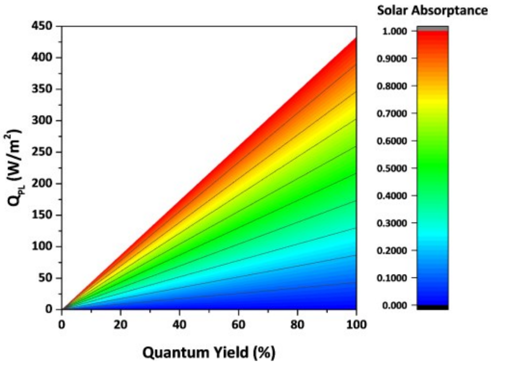
Optimization: Re-emitted energy through photoluminescence(PL) effect

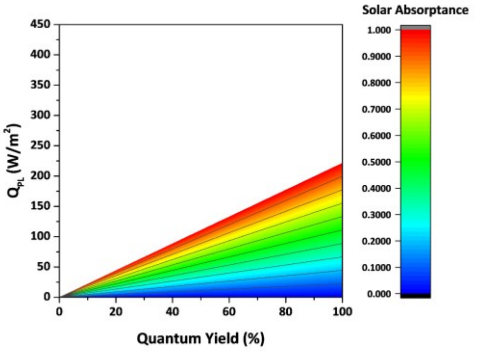
Correlation between Re-emitted Energy (Q_{PL}), Solar Absorptance, and Quantum Yield(QY) in a representative summer day in Observatory Hill Station, Sydney

❖Absorption Edge Wavelength($\lambda_{Absorption\ Edge}$): 1000 nm

❖Average Solar Irradiation: 878 kWh/m2 during summer & 449 kWh/m2 during winter.

❖Maximum Re-emitted Energy through photoluminescence : 433 kWh/m2 during summer & 221 kWh/m2 during winter (49% of the incoming solar irradiation)





Optimization: Re-emitted energy through photoluminescence(PL) effect

The transmission and thermalization losses determine the theoretical limit for fluorescent cooling potential

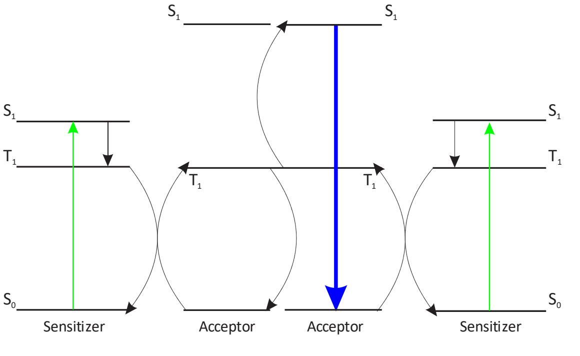
❖**Transmission Loss:**

1. Up conversion of two photons with energies lower than the bandgap energy into one higher than the bandgap energy photon.

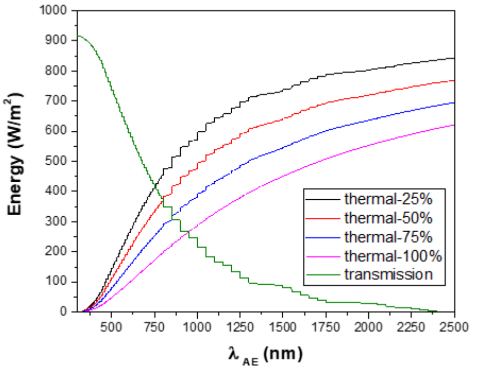
2. Transmission loss can be minimized through application of a NIR-reflective material as base layer.

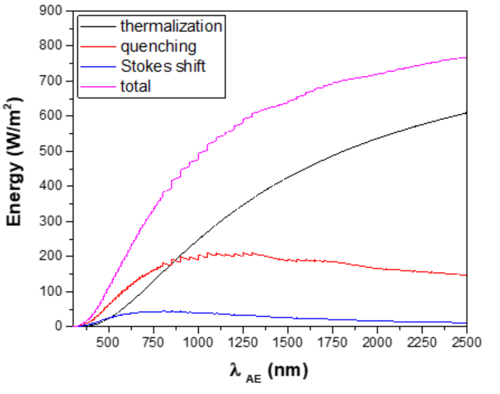
❖ **Thermalization Loss:**
Down conversion of one high energy photon into two lower energy photons.

❖ **Quenching Loss:**
1.Reducing reabsorption by application of surface ligands around QDs core,
2. Controlling surface defects.



Optimization: Re-emitted energy through photoluminescence(PL) effect





Left: Impact of λAE on thermal and transmission losses in Stokes shift fluorescent materials.
Right: Impact of λAE on thermal losses in Stokes shift fluorescent materials

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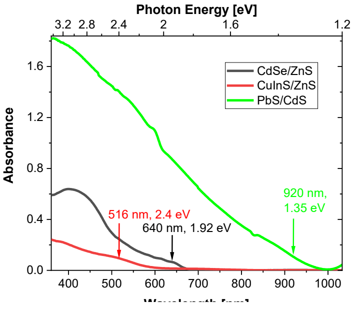
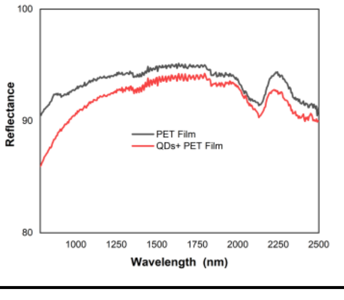
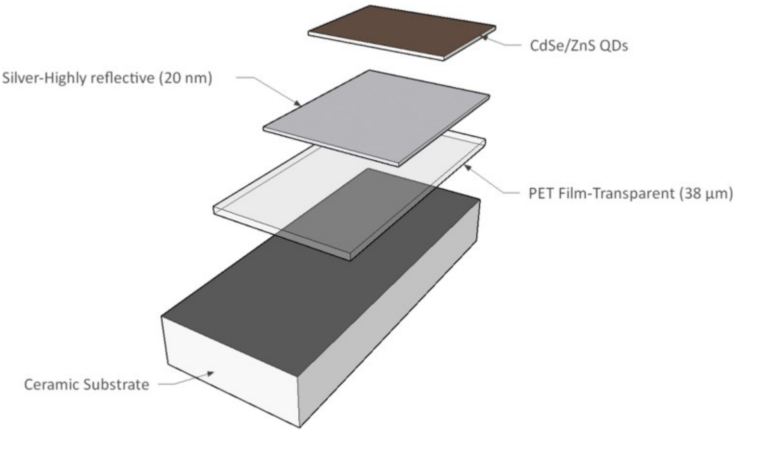
Reducing transmission loss through integration with NIR-reflective materials







S. Garshasbi, S. Huang, J. Valenta, M. Santamouris, "On the combination of quantum dots with near-infrared reflective base coats to maximize their urban overheating mitigation potential", Solar Energy, 2020, 211, 111-116, https://doi.org/10.1016/j.solener.2020.09.069

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