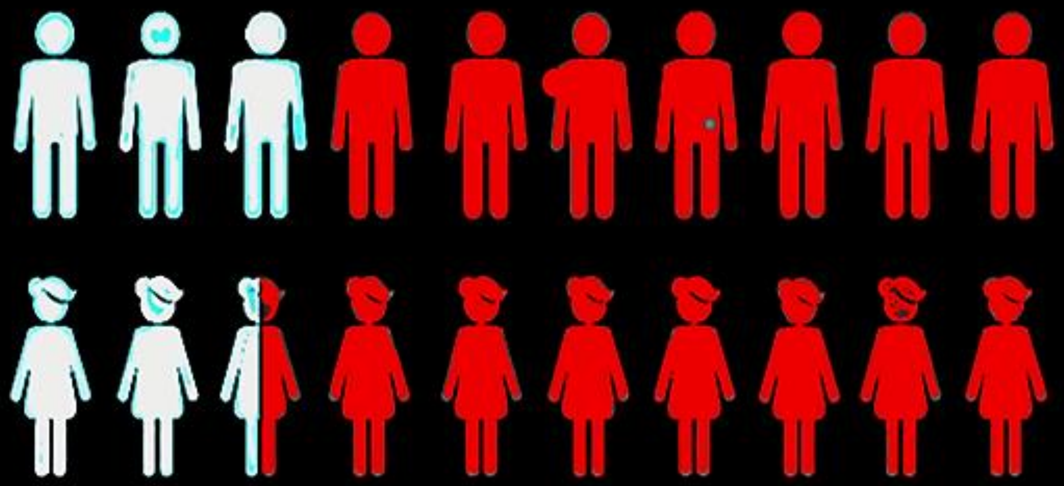
Quantifying the energy impact of heat mitigation technologies at the urban scale. The Riyadh mitigation project

On the magnitude of Urban Climate Change, Its impact on Energy, Health, Productivity, Vulnerable Population, Economy and Environmental Quality. Heat Mitigation and Adaptation Potential and Proposals to Counterbalance Urban Heat

M. Santamouris, UNSW, Sydney, Australia



13,000 OVERHEATED CITIES

1.7 BILLION PEOPLE UNDER SEVERE OVERHEATING

THREE TIMES MORE OVERHEATING HOURS SINCE 1980

118 BILLION OVERHEATING MAN HOURS

C. Tuholske *et al.*, “Global urban population exposure to extreme heat,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 118, no. 41, pp. 1–9, 2021, doi: 10.1073/pnas.20247921

Rises the cooling energy consumption in cities ,

Decreases the efficiency of power plants

Rises the peak electricity demand

Increases the emission of pollutants of the power plants

Increases the concentration of ozone

Intensifies heat related mortality and morbidity

Causes serious Mental Health Problems

Lowers the productivity of population

Increases the Risk of Accidents

Affects the survivability of vulnerable population

Increases the Cooling Energy Consumption

Urban overheating is inducing an additional energy penalty at the city scale close to 0.74 kWh/m2 /°C, while the average energy penalty per person, is close to 237 (± 130) kWh/p

Increases the Peak Electricity Demand

The peak electricity rise per degree of temperature increase varies between 0.45% and 4.6%, corresponding to an additional electricity penalty close to 21Watts (± 10.4) per degree of temperature increase and per person

Decreases the Efficiency of Power Plants

A 1 °C rise of the ambient temperature reduces the power output of thermal and nuclear power stations by 0.6%

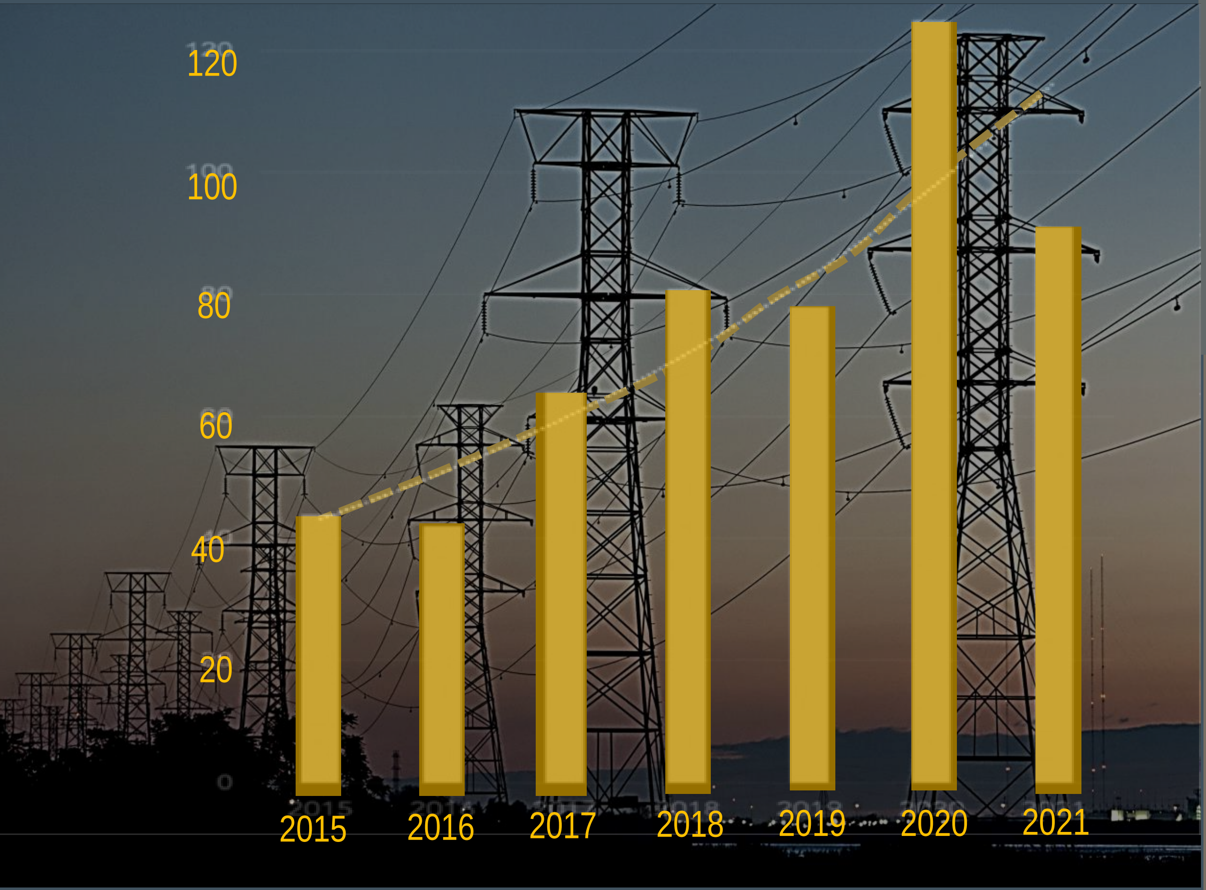
M. Santamouris, “Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change,” *Energy Build.*, , 2020,

On August 2022, the UK Met Office recorded the country's first-ever temperature above 40 degrees Celsius (104 degrees Fahrenheit) at London's Heathrow Airport just before 1 p.m., as temperatures were still rising.

High demand sent power prices in the UK up 5% in one day.

Across the Channel, things have been even more volatile. Europe's heat wave has reduced France's available nuclear power, as the river water used to cool nuclear plants became too hot to be effective.

As a result, day-ahead baseload power prices settled at 610 euros per megawatt-hour — about 10 times higher than prices from 2017 to 2021.



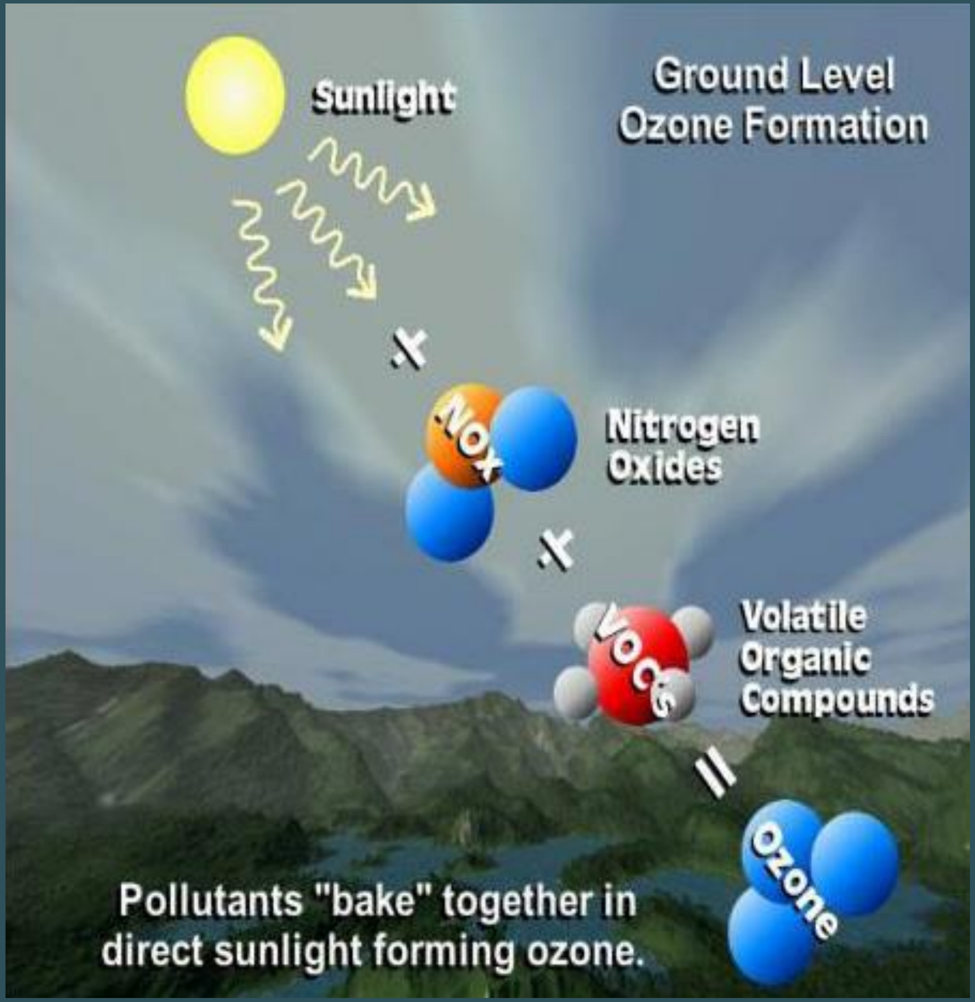
The incidence of electrical grid failure or “blackout” events is increasing all around the world

In USA, since 2015, when the U.S. Energy Information Administration commenced monthly reporting on major blackout events ,the number of such events nationwide has more than doubled, increasing by 151% between 2015−16 and 2020−21

In June of 2021,electrical grid failures because of a very high intensity heat wave in in the Pacific Northwest zone of USA resulted in at least:

- 600 excess deaths,
- 3500 emergency hospital visits, and
- Loss of electricity to tens of thousands of citizens in the area.

How Blackouts during Heat Waves Amplify Mortality and Morbidity Risk Brian Stone, Jr.,* Carina J. Gronlund, Evan Mallen, David Hondula, Marie S. O'Neill, Mayuri Rajput, Santiago Grijalva, Kevin Lanza, Sharon Harlan, Larissa Larsen, Godfried Augenbroe, E. Scott Krayenhoff, Ashley Broadbent, and Matei Georgescu, Env Research and Technology, 2023



Overheating affects the urban environmental quality increasing the concentration of harmful pollutants.

Higher urban temperatures accelerate the formation of ozone precursors like VOC's and NOx combining photochemically to generate ground level ozone.

Ozone is toxic and an oxidant affecting the human respiratory and cardiovascular systems.

The expected future increase of the ambient temperature is expected to further increase the concentration of the ground level ozone and the frequency of future severe ozone episodes, as well as the concentration of other pollutants.

It is estimated that the frequency of severe ozone episodes in four Canadian cities may increase up to 50% by 2050 and 80% by 2080.

Urban overheating obliges utilities to operate power plants for an extended period to satisfy the peak electricity demand

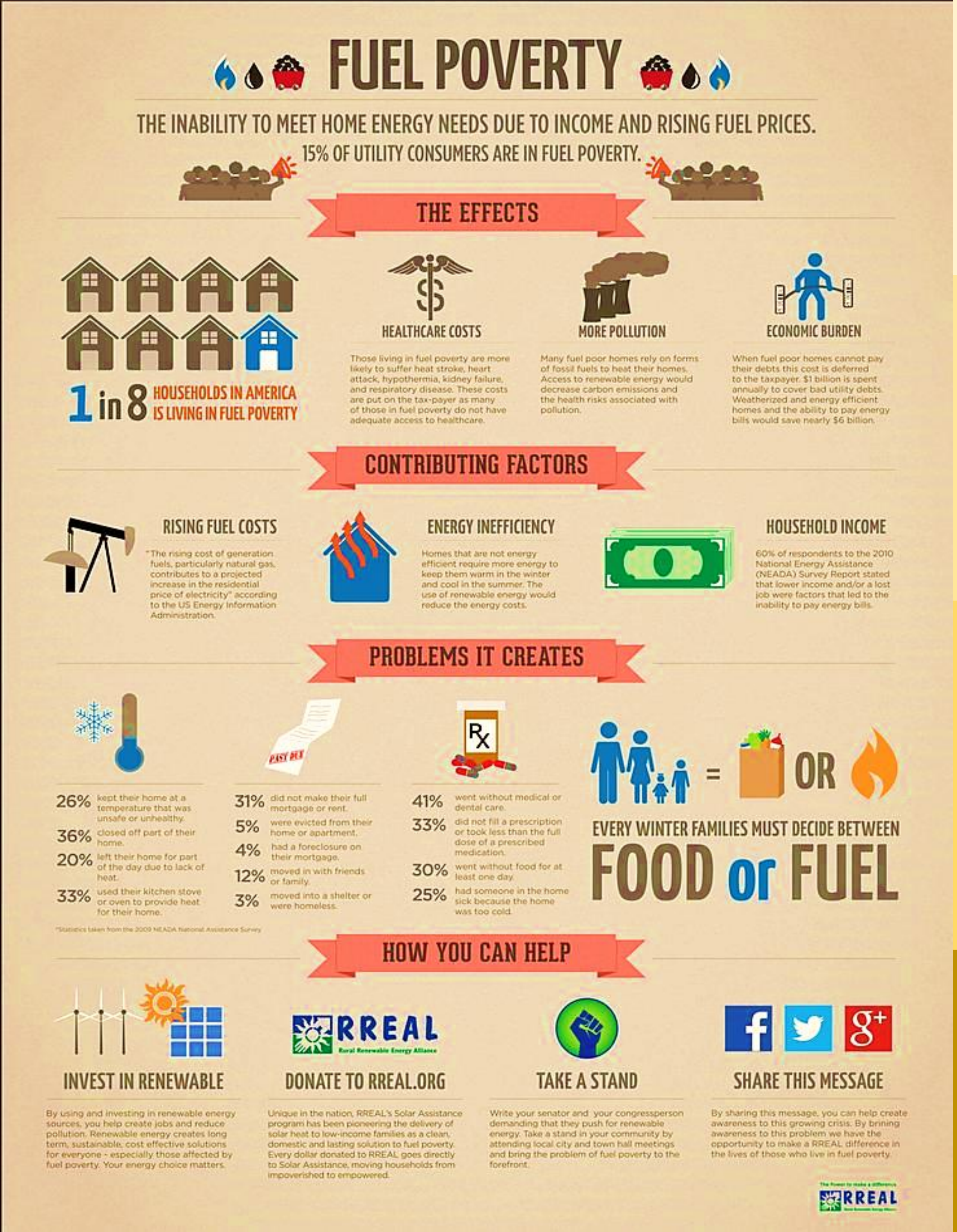
Increased operation of thermal power plants significantly rises the emissions of pollutants and increases the concentration of secondary pollutants like the ground level ozone.

Each degree of temperature rise in the Eastern United States during the period between 2007-2012, resulted in a rise by:

3.35%/°C ±0.50%/°C of the SO_2 emissions,
3.32%/°C ±0.36%/ °C rise in CO_2 emissions, and a
3.60%/°C ±0.49%/°C increase in NO_X emissions.

It is predicted that in 2050 the corresponding NOx emissions may increase by 16%, and the SO_2 emissions by 18%.

M. Santamouris, "Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change," *Energy Build.*, vol. 207, 2020



Low-income population lives in deprived urban zones with high overheating. Urban Overheating results in high mortality, energy cost and discomfort.

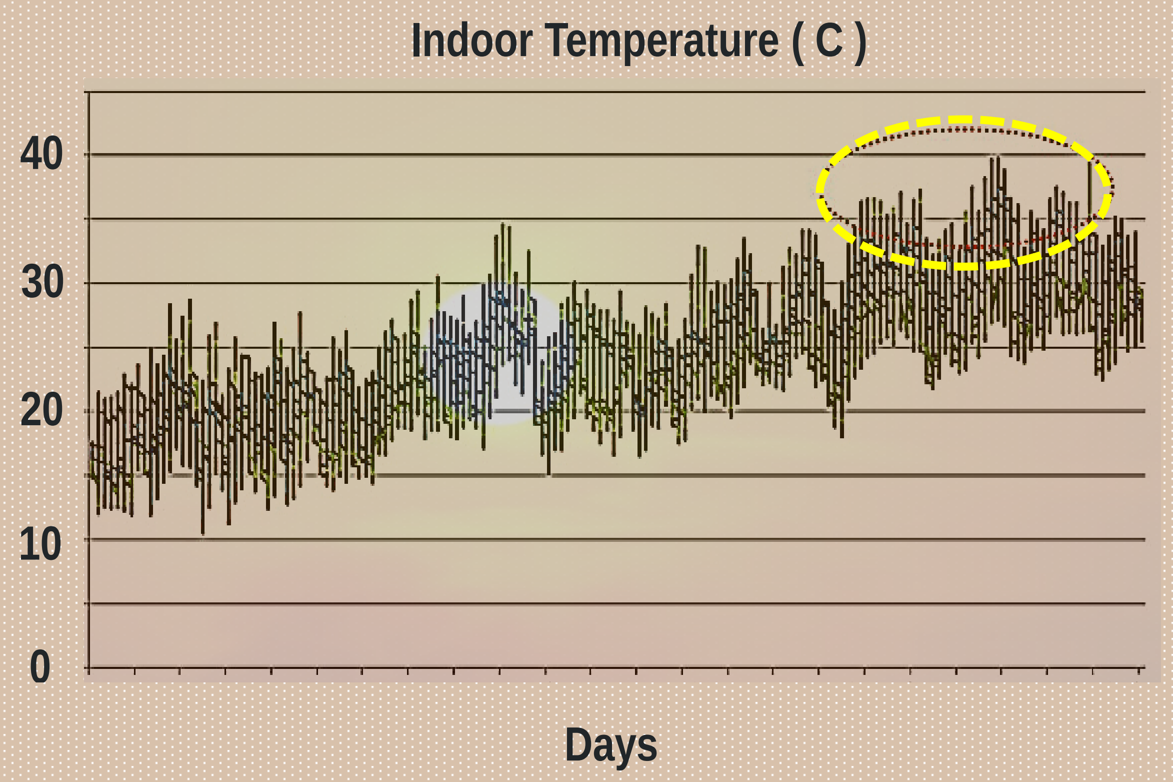
Overheating affects the urban socioeconomic and biophysical vulnerability and has a serious impact on low-income population.

Vulnerable population lives in districts of disproportionately high UHI intensity, excess heat stress, higher risk of heat related mortality and significant socioeconomic vulnerability

A significant correlation between exposure to extreme heat and the socioeconomic vulnerability exists for several cities resulting in almost twice the mortality risk in the deprived districts.

Vulnerable population lives in buildings of considerably lower thermal quality. Extreme indoor temperatures, 35-40°C, are recorded during extreme events in low-income houses.

Only 2% of the necessary cooling load is covered by low-income population in Portugal, while in Greece the cooling cost for low-income households is approximately double the average cost.



Rich experimental data exist in the developed countries regarding the indoor environmental quality of low-income houses during the period of high ambient temperatures.

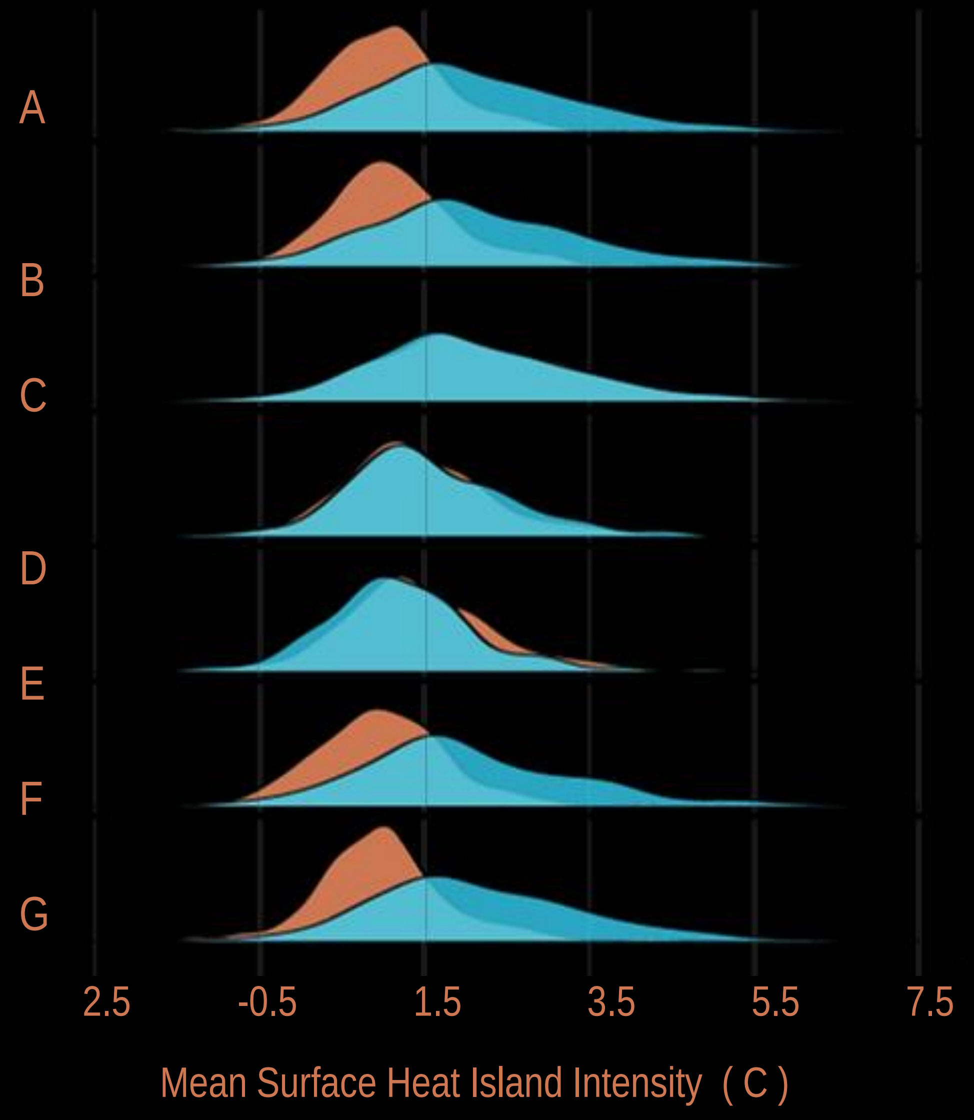
Continuous measurements of the indoor ambient temperature and CO_2 concentration, are performed in 110 low-income buildings in Western Sydney and rural NSW, for about 12 months.

It is found that during the summer period and not during a heat wave, indoor temperature was close to 40 C.

In parallel, the indoor concentration of CO_2 was up to 4 times higher than the threshold acceptable levels.

During the winter period, indoor temperature was as low as 5- 7 C.

Shamila Haddad, Riccardo Paolini, Afroditi Synnefa, Lilian De Torres, Deo Prasad, Mattheos Santamouris : Integrated assessment of the extreme climatic conditions, thermal performance, vulnerability, and well-being in low-income housing in the subtropical climate of Australia, Energy and Buildings, 272, 112349, 2022



Results from 175 cities in USA correlating the magnitude of the surface Urban Heat Island against social and demographic characteristics, shown that immigrants, black and Hispanic population and vulnerable groups live in urban zones presenting a much higher UHI Intensity

A :Non Hispanic whites vs all people in color

B : Above vs Below Poverty

C : Below Poverty against all people in color

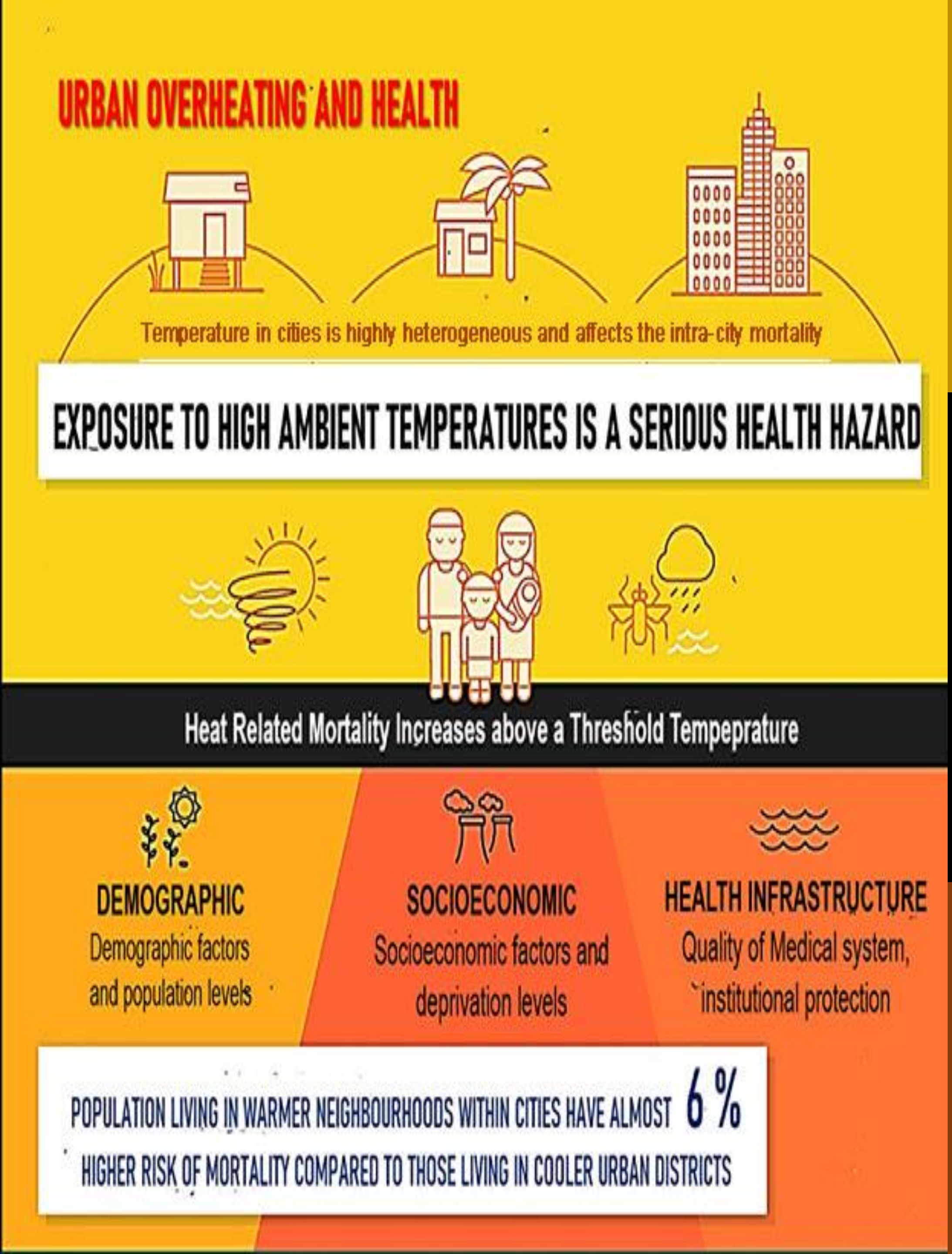
D : Over 5 vs under 5

E : Over vs Under 65 y old

F : Over 65 White against all people in color

G : Under 5: Non Hispanic whites vs all people in color

A. Hsu et al : Disproportionate Exposure to Urban Heat Island intensity across Major US cities, Nature Communications,

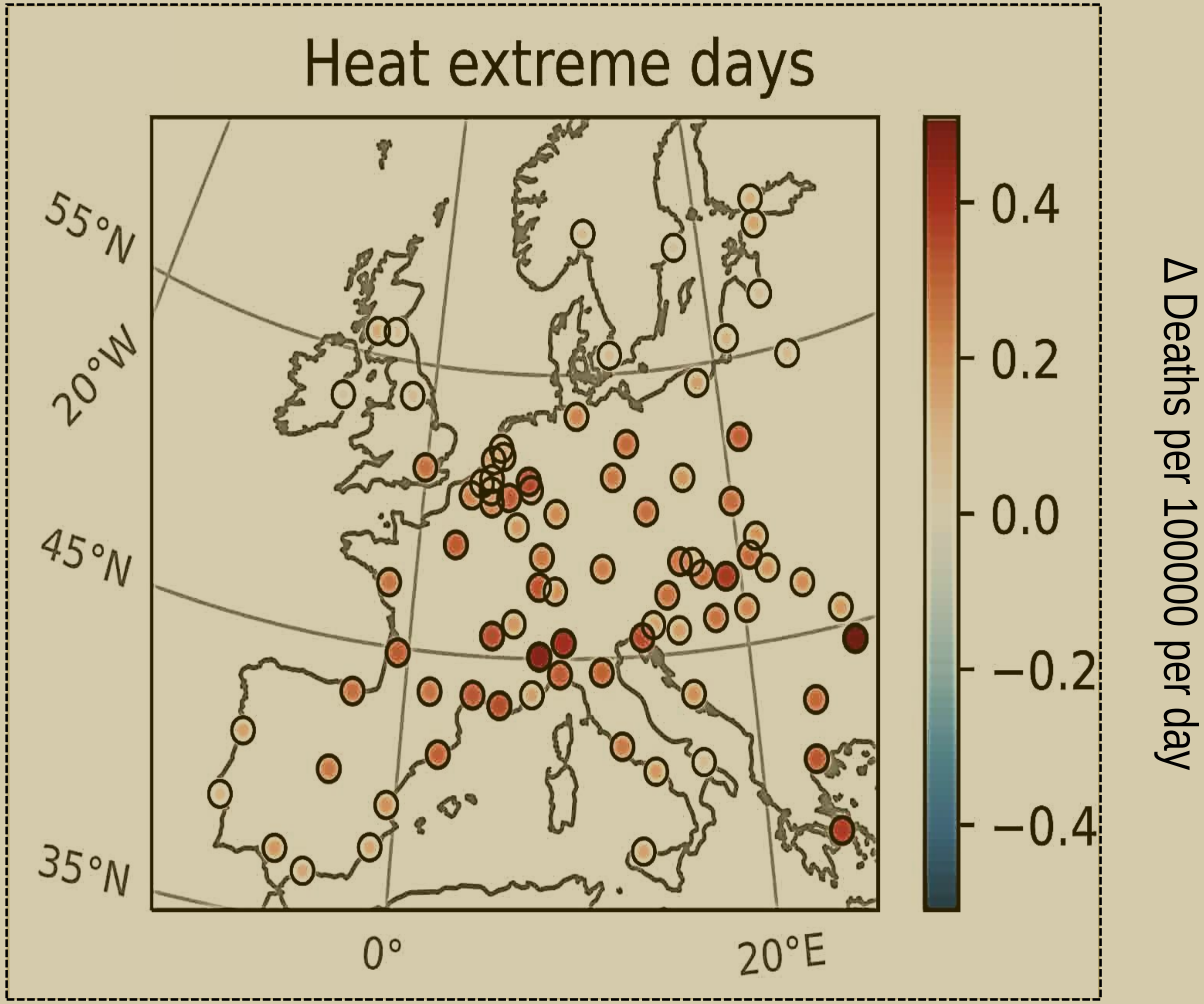


When exposed to temperature beyond a certain threshold, the human thermoregulation system cannot offset the impact of extreme heat resulting in increased global mortality and morbidity

Heat related morbidity and mortality caused by the local climate change, is highly alarming, and it seems to be one of the current and future peak scientific topics .

Elderly is the most vulnerable population group
Those with preexisting health problems like respiratory, cardiovascular, or mental health problems
Those using medication that affects thermoregulation, and
Those ‘lacking in economic assets and access to public support systems, with diminished physical or cognitive capacities to respond to warnings and missing strong and enduring social support systems like social isolated people, and those living in hazardous places’

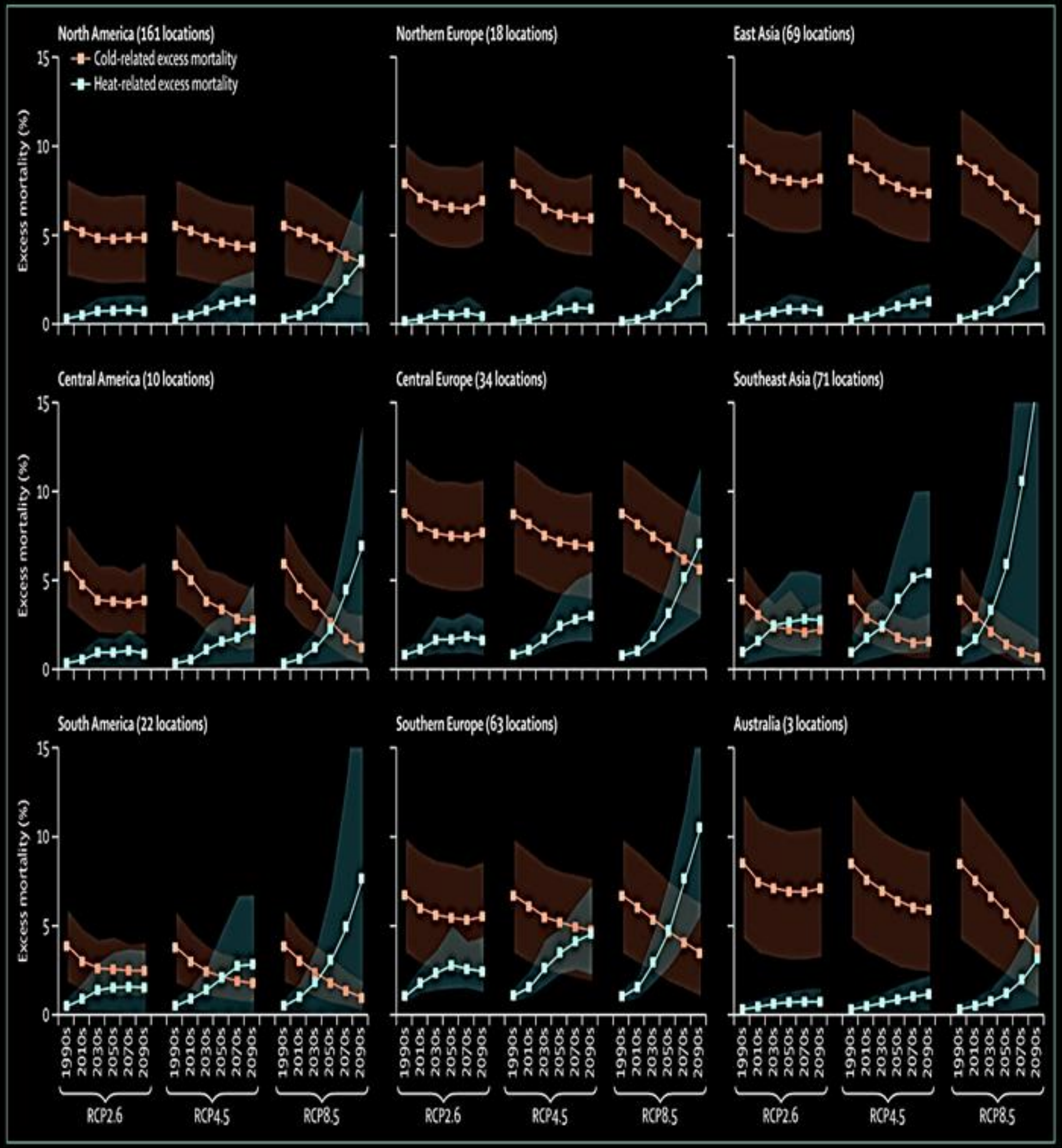
According to the existing epidemiological records almost 59,114 people passed away between 2000 and 2007 during 52 extreme heat events around the world



UHI is found to have a very high impact on mortality risk in 85 European cities, during heat extreme days, with a median of 0.25 additional deaths per 100,000 adult city inhabitants per day, or 45% increase in comparison to rural areas, over each city's warmest 2% (22) days in 2015–2017

Acute impacts are found during heat extremes, with a 45% median increase in mortality risk associated with UHI, compared to a 7% decrease during cold extremes. However, protracted cold seasons result in greater integrated protective effects. On average, UHI induced heat-/cold-related mortality is associated with economic impacts of €192/€−314 per adult urban inhabitant per year in Europe

Huang et al : Economic valuation of temperature-related mortality attributed to urban heat islands in European cities, Nature Communications 2023



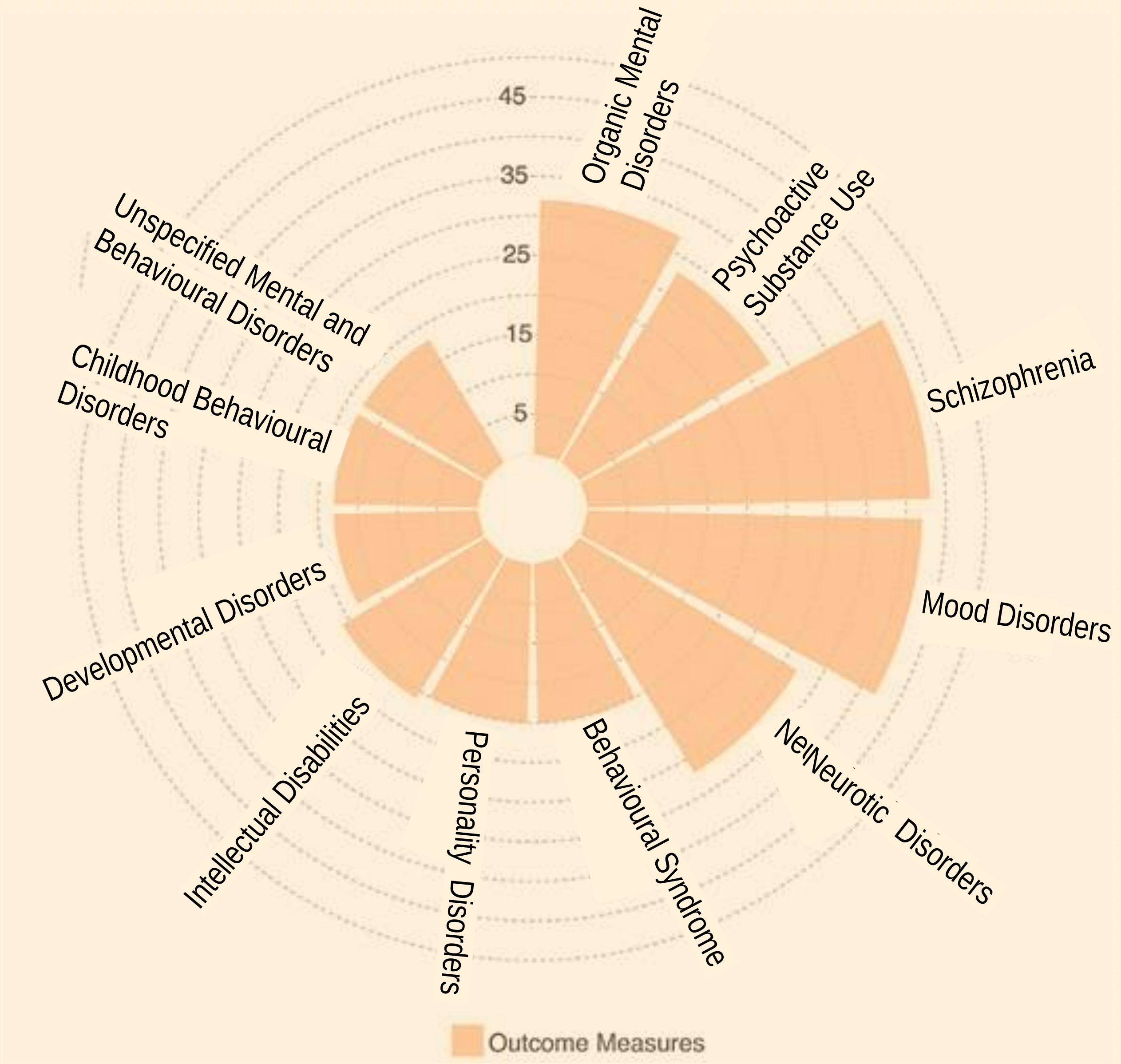
Lancet has published an extended epidemiological investigation on the potential health effects of higher ambient temperatures under various climate change scenarios, socioeconomic and demographic conditions , public health status and levels of economic development. services.

'The study indicates that, in high-emission scenarios, most regions are projected to experience a steep rise in heat-related mortality that will not be equaled by a reduction in cold-related deaths, resulting in a substantial positive net increase in mortality.

However, the potential impact varies across areas, and populations living in warmer and potentially poorer regions are expected to sustain an increased burden.

Furthermore, the increase in temperature-related excess mortality would be substantially reduced in scenarios involving mitigation strategies to limit greenhouse gas emissions and further warming of the planet, and stricter mitigation approaches are associated with larger benefits'.

www.thelancet.com/planetary-health Vol 1 December 2017



Hea

Numerous studies have revealed critical associations between temperature extremes, and mental illness

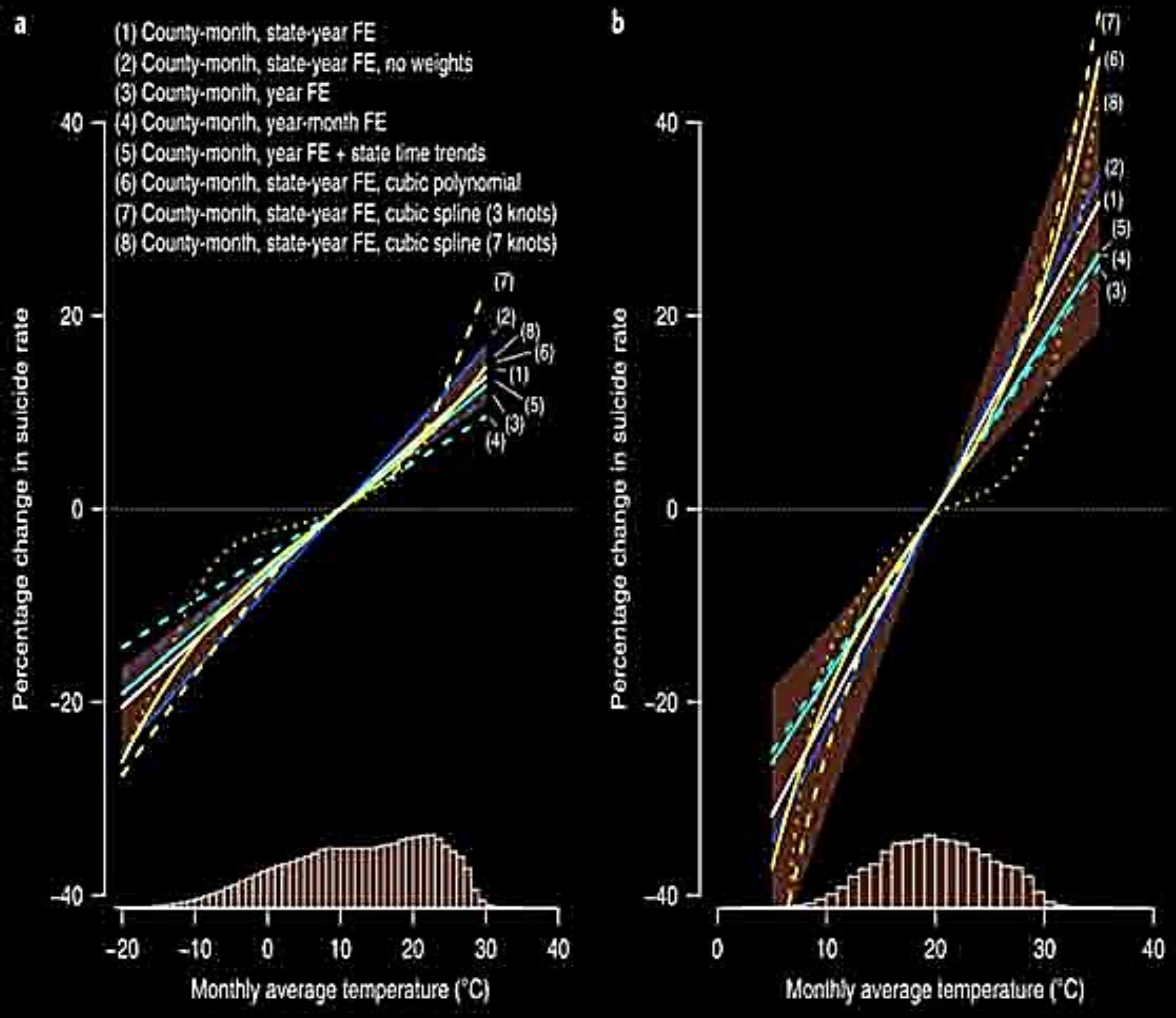
Three types of climate-related events (acute, subacute, and long-lasting changes) on mental health are identified.   Extreme heat events that occur in summer could pose a serious risk to human mental conditions.

Meta-analysis showed that heatwaves and extreme high temperatures were associated with higher risk of schizophrenia, mood disorders, neurotic disorders.

A strong association between increases apparent temperature and elevated risk of Mental Behavioral Disorders.

A 99th percentile high temperature was associated with increased schizophrenia risk

D.Li et al: Climatic and Meteorological Exposure and Mental and Behavioural Health. A systematic Review and Metanalysis. Science of the Total Environment, 2023.

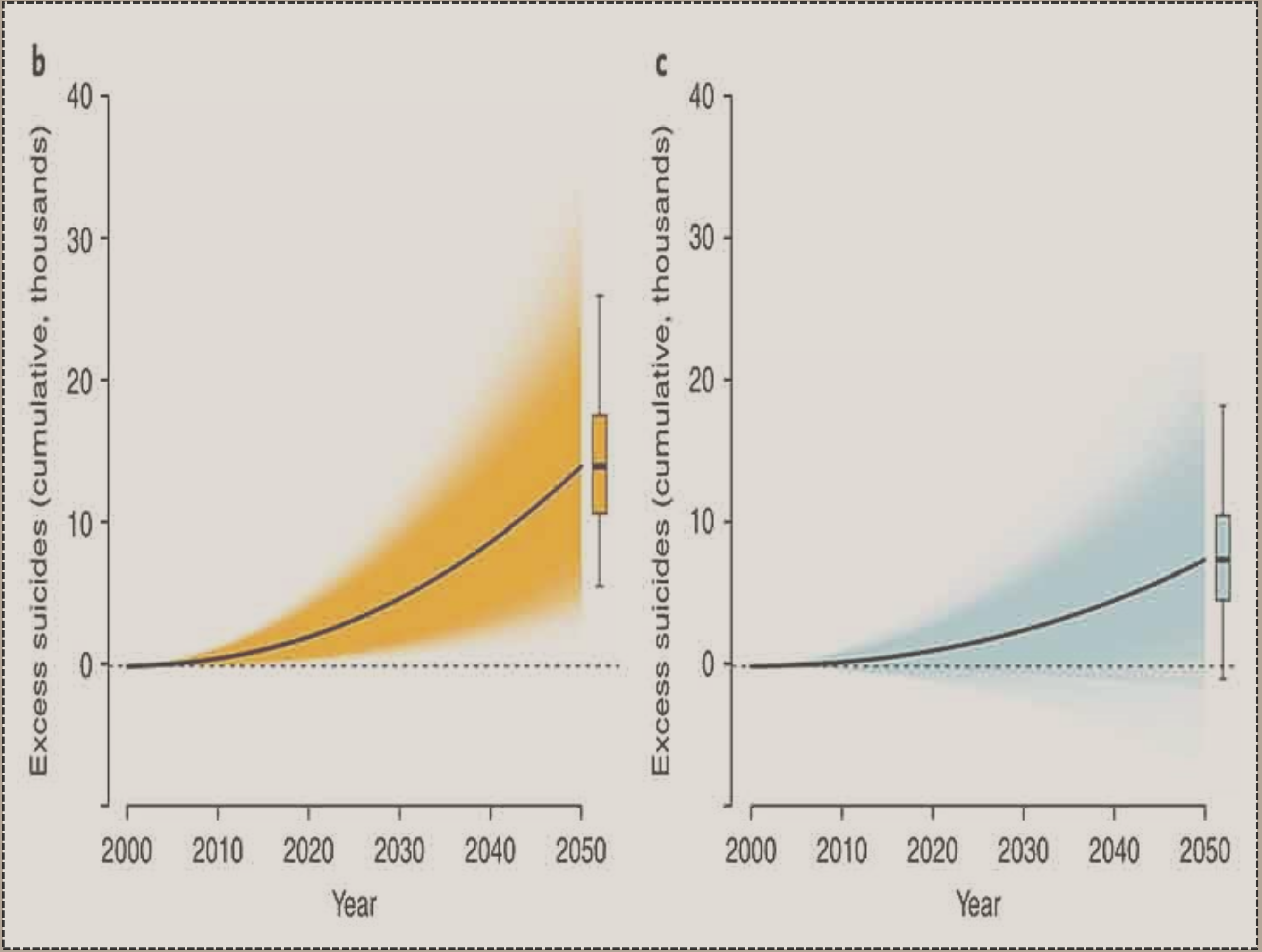


Using comprehensive data from multiple decades for both the United States and Mexico, it is found that suicide rates rise 0.7% in US counties and 2.1% in Mexican municipalities for a 1 °C increase in monthly average temperature.

This effect is similar in hotter versus cooler regions and has not diminished over time, indicating limited historical adaptation.

In contrast to all-cause mortality, suicide increases at hot temperatures and decreases at cold temperatures; also unlike all-cause mortality, the effect of temperature on suicide has not decreased over time and does not appear to decrease with rising income or the adoption of air conditioning.

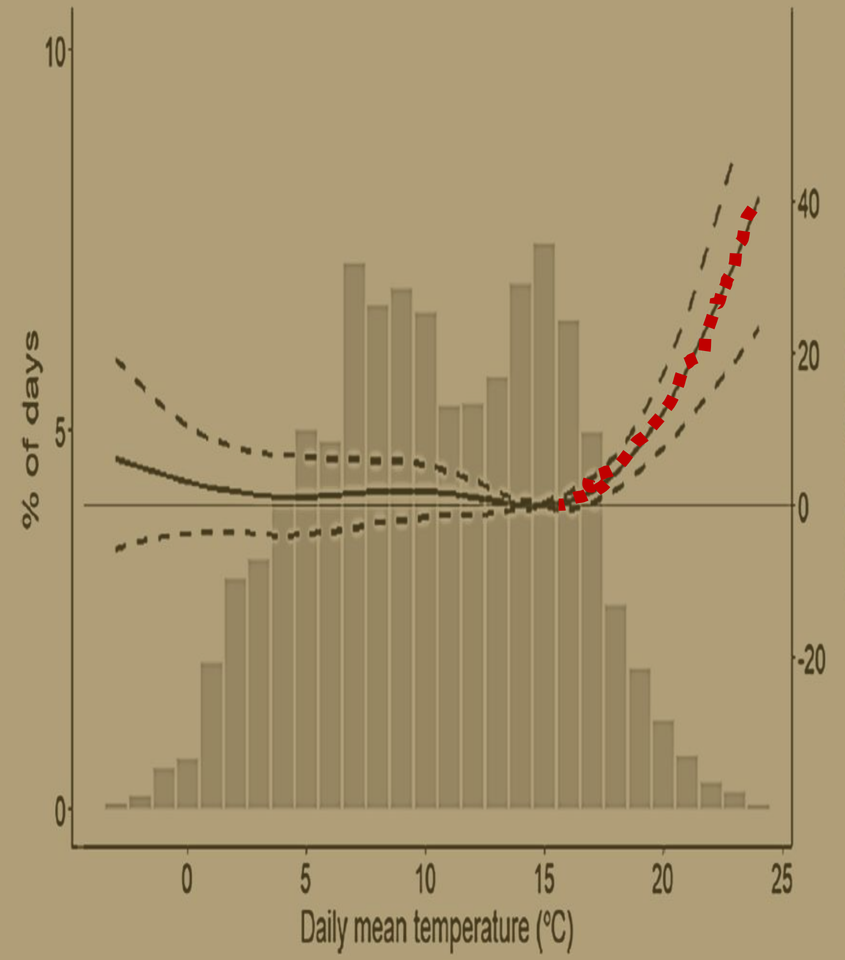
Burke et al : High Temperatures Increase Suicide Rates in the USA and Mexico, Nature Climatic Change 2018



It is projected that unmitigated climate change (RCP8.5) could result in a combined 9–40 thousand additional suicides across the United States and Mexico by 2050,
representing a change in suicide rates comparable to the estimated impact of economic recessions, suicide prevention programs or gun restriction laws

In absolute value, the effect of climate change on the suicide rate in the United States and Mexico by 2050 is roughly two to four times the estimated effect of a 1% increase in the unemployment rate in the European Union

Burke et al : High Temperatures Increase Suicide Rates in the USA and Mexico, Nature Climatic Change 2018



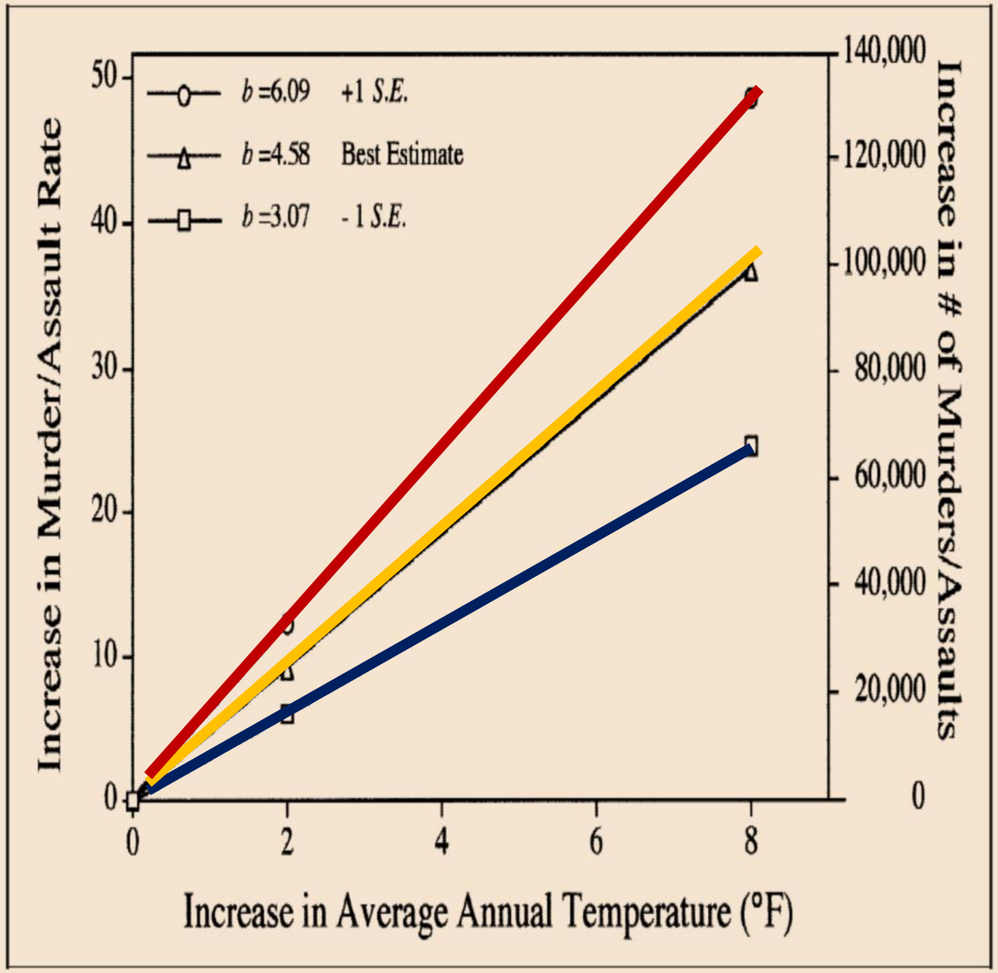
A study involving Medicare-enrolled individuals living in New England found that each 1.5°C, increase in summer temperature was associated with a 12% increased risk for dementia-associated hospitalization

Another similar study in England has associated the daily ambient temperature and acute hospitalisation because of dementia.
It is found that for each degree increase above 17 C, the risk of dementia admission increased by 4.5 %

Wei Y, Wang Y, Lin C-K et al. (2019) [Associations between seasonal temperature and dementia-associated hospitalizations in New England](). ***Environment International*** **126, 228-233.**

And

Gong et al : Current and Future Burdens of Heat Related Dementia Hospital Admissions in England, Environmen International 2022



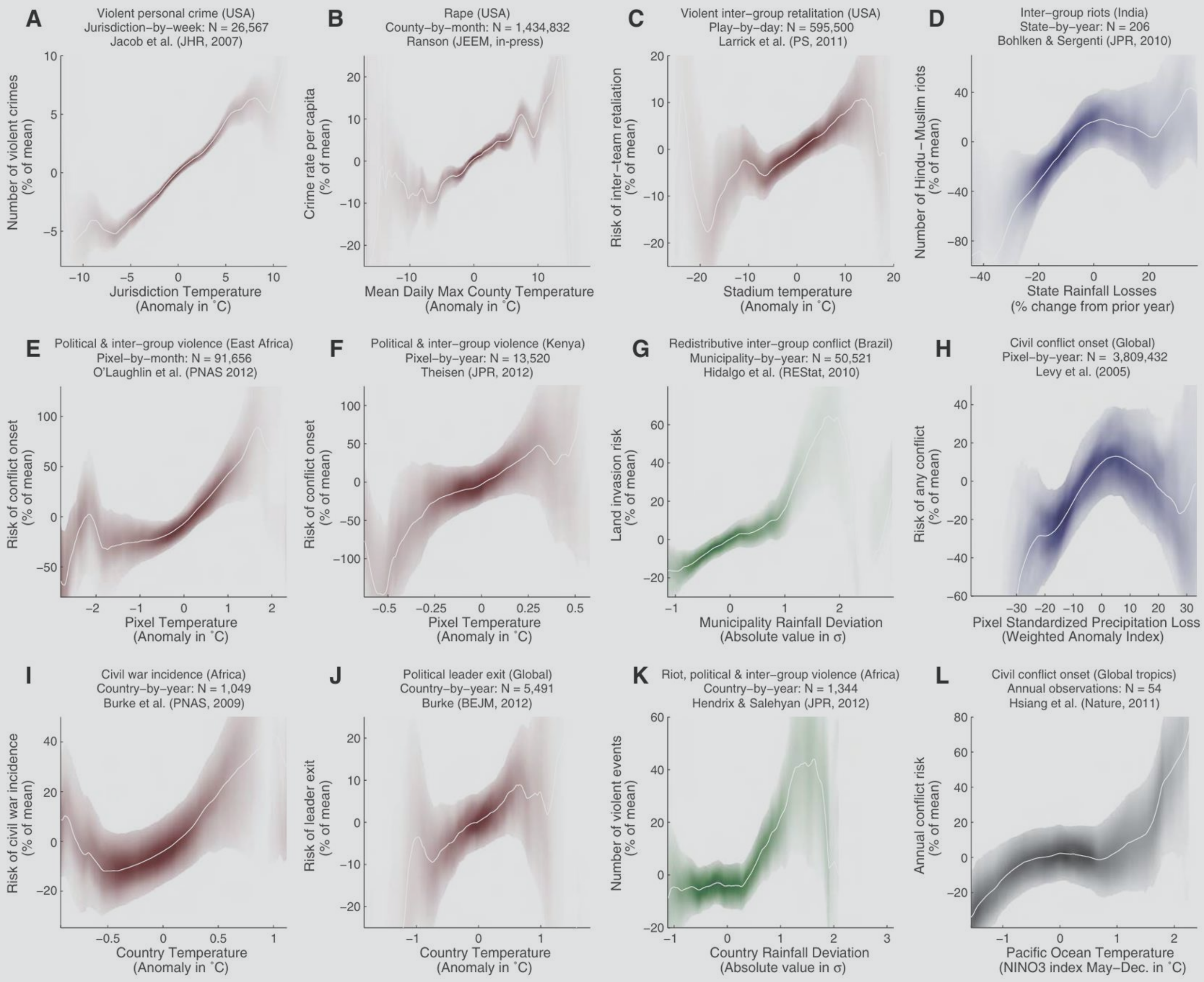
Urban Overheating has a serious adverse impact on wellbeing and threats mental health.

Mental health impacts are expected to arise from climate-related economic and social losses and anxiety and distress associated with overheating.

It is found that there is a statistically significant correlation between the increase of the ambient temperature and the corresponding increase of murder and assault rate.

Similar statistics have been observed for numerous cities around the world during period of extreme temperature.

Heat and Violence. Article *in* Current Directions in Psychological Science · February 2001 DOI: 10.1111/1467-8721.00109

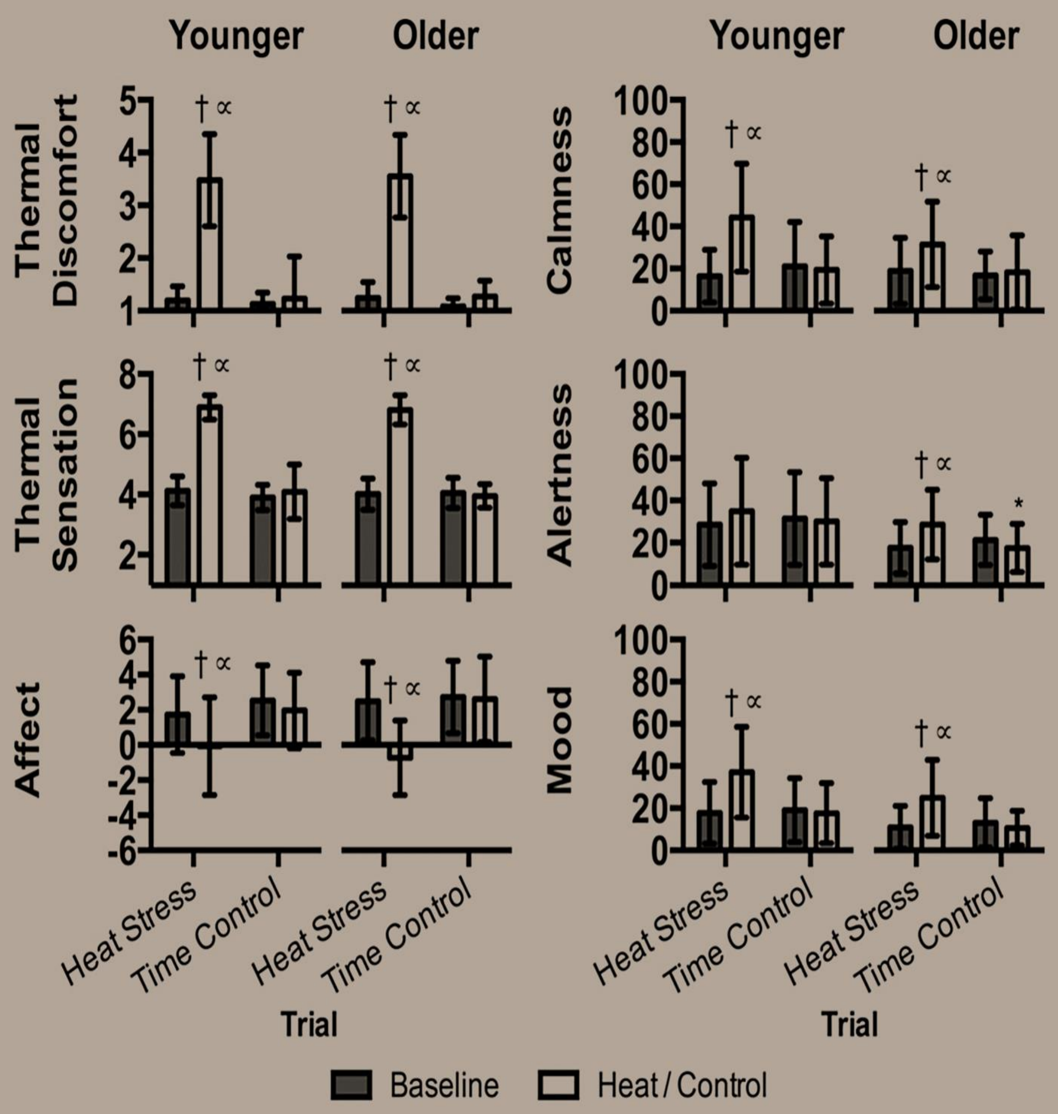


Empirical Studies indicate that climatic variables have a large effect on the risk of violence or instability in the modern world

Deviations from normal mild temperatures systematically increase the risk of conflict, often substantially. This relationship is apparent across spatial scales ranging from a single building to the globe and temporal scales ranging from the anomalous hour to an anomalous millennium.

Each 1 SD change in climate toward warmer temperatures increases the frequency of interpersonal violence by 4 % and intergroup conflict by 14 %.

Hsiang et al : Quantifying the Influence of Climate on Human Conflict. Science, 2013

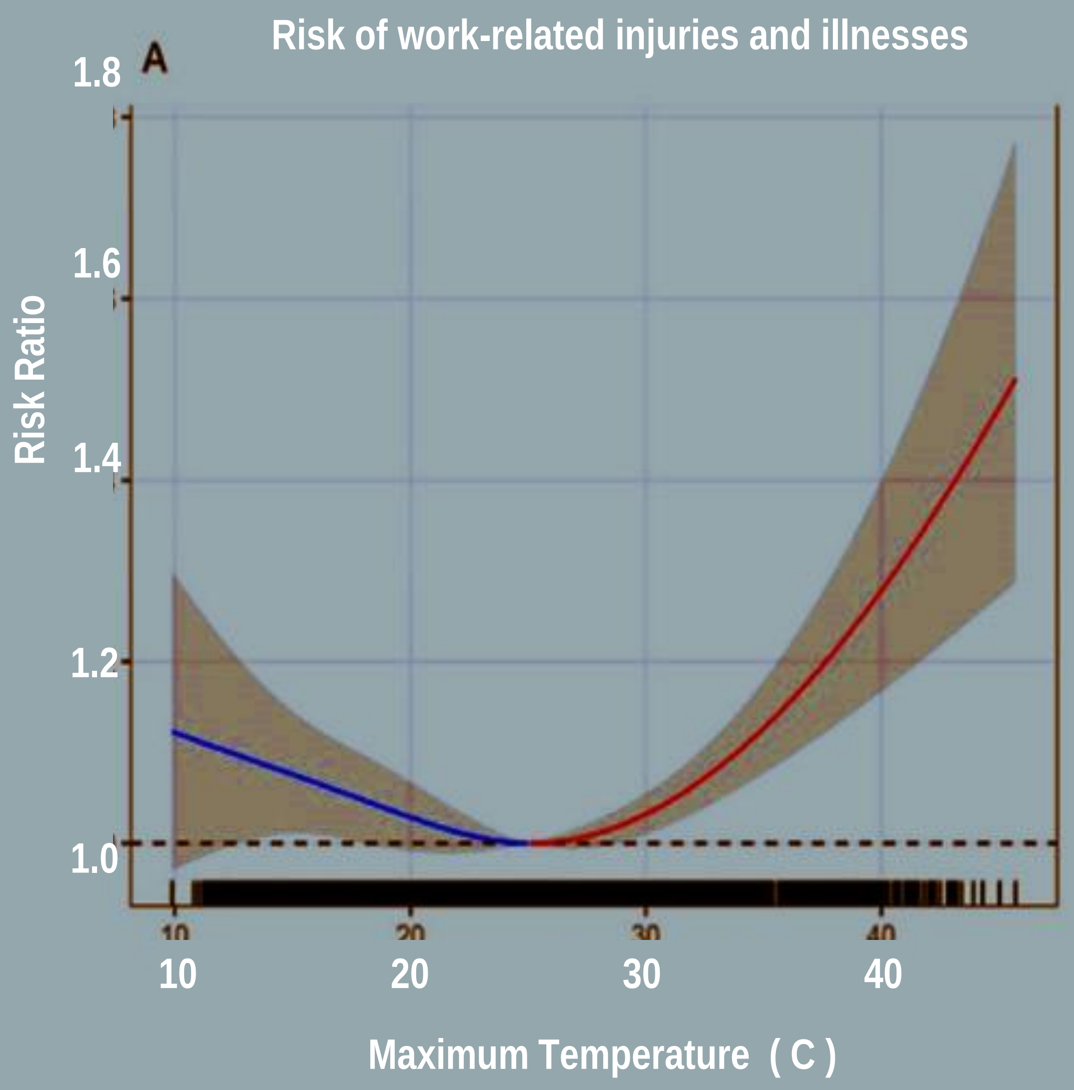


A study tested the hypothesis that attention, memory, and executive function are impaired largely in passively heat-stressed older adults than in passively heat-stressed younger adults.

It is observed that heat stress-induced impairments in cognitive function are amplified with age, this might suggest that the contribution of cognitive factors to the risk of morbidity and mortality during heat waves would be exacerbated in older adults.

Moderate increases in body temperature during passive heat stress do not differentially compromise cognitive function in younger and older adults.

Zachary J. Schlader et al: Cognitive and perceptual responses during passive heat stress in younger and older adults, Am J Physiol Regul Integr Comp Physiol308: R847–R854, 2015.

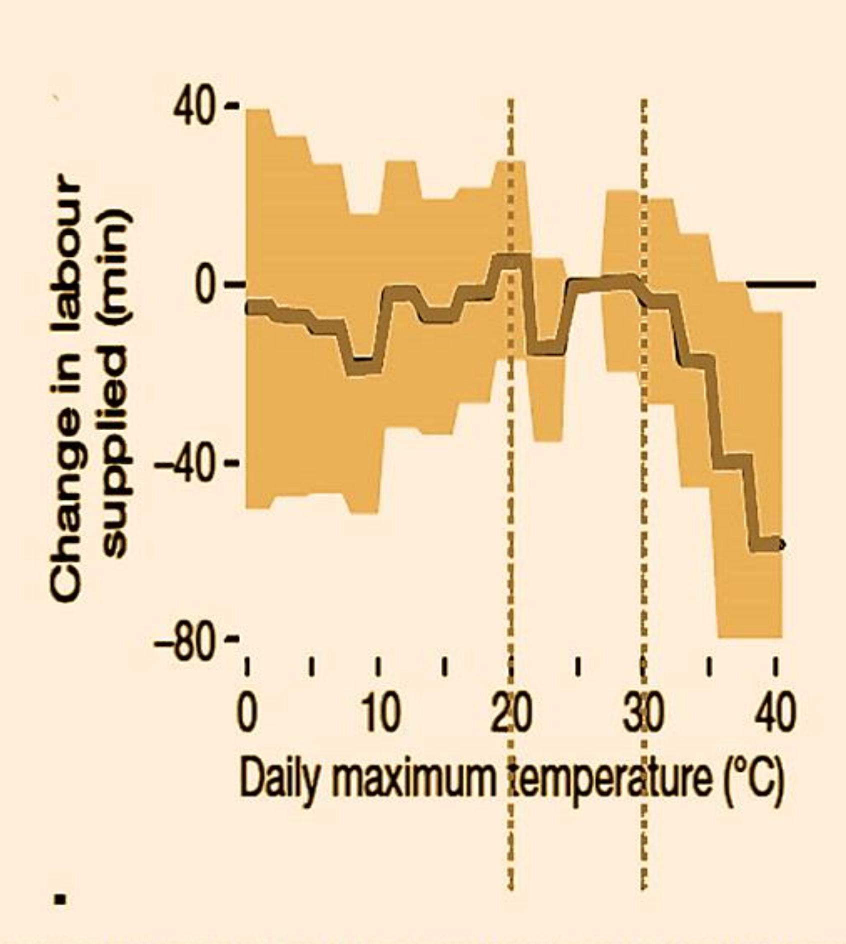


Occupational Heat Stress refers to the physiological effect of environmental heat stress on the body and has a major impact on the ability of workers to live healthy and productive lives.

Studies performed in 30 countries including 447 million workers found that:

Individuals working a single work shift under heat stress were 4 times more likely to experience occupational heat strain than individuals working in thermoneutral conditions.

The effects of ambient temperatures on the risk of work-related injuries and illnesses: Evidence from Adelaide, Australia 2003–2013. Blesson M. Varghesea, Adrian G. Barnettb, Alana L. Hansena, Peng Bia, Scott Hanson-Easeya,Jane S. Heyworthc, Malcolm R. Simd, Dino L. Pisanielloa Environmental Research 170 (2019) 101–109



Recent research found that labour supply and human productivity may decrease up to 60% when ambient temperature exceeds 30-35 C

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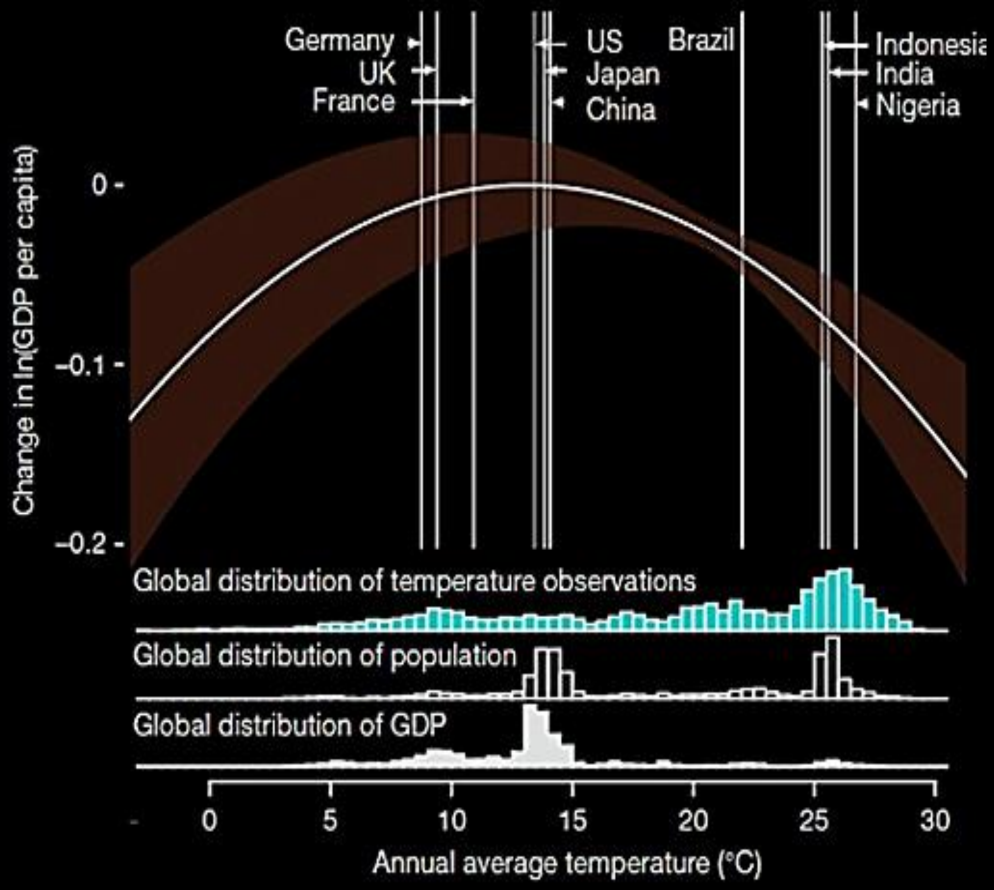
Graff Zivin, J. & Neidell, M. Temperature and the allocation of time: Implications for climate change. J. Labor Econ. 13, 1–26 (2014).



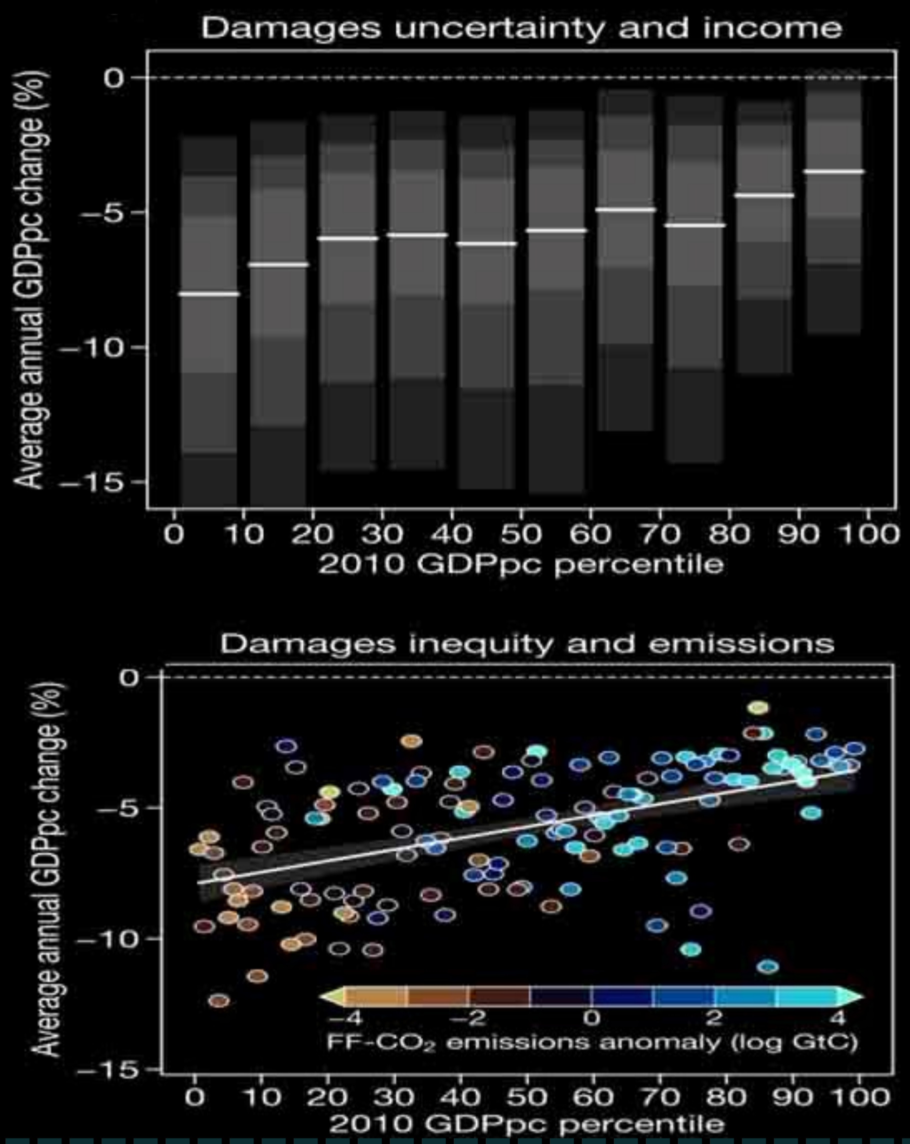
United States lose approximately $100 billion annually from heat-induced loss in labor productivity.

Economy in U.S. grows at a slower pace during hot summers. The annual growth falls 0.15 to 0.25% for every 1 F increase of the average summer temperature.

Warming is expected to reshape the global economy by reducing average global incomes by roughly 23% by 2100 and widening global income inequality, relative to scenarios without overheating.

About 1 Million work life-years are projected to be lost by 2030 due to operational heat stroke fatalities with 70 million work life-years lost because of reduced labour productivity.

Global non-linear effect of temperature on economic production, Marshall Burke, Solomon M. Hsiang*& Edward Miguel, 1 2 N O V E M B E R 2 0 1 5 | VO L 5 2 7 | N AT U R E | 2 3 5



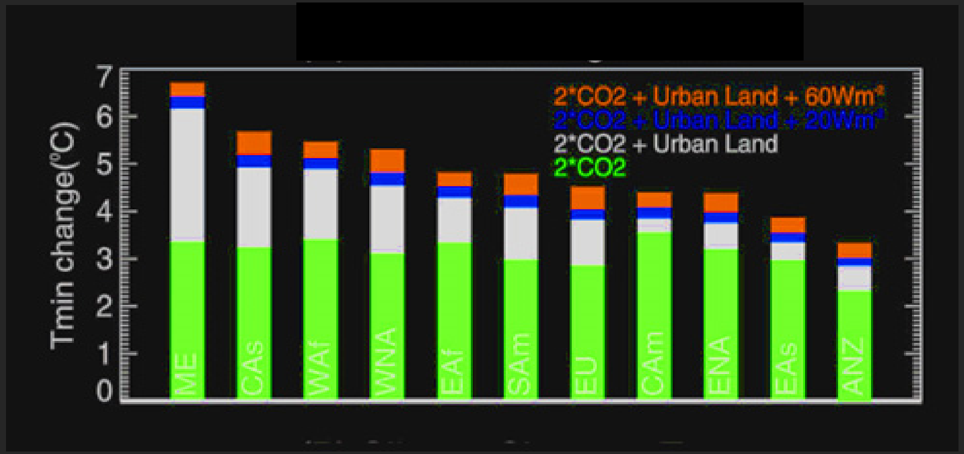
Increases in extreme heat from anthropogenic global warming pose alarming risks to human well-being. These risks are particularly acute in the poorest and warmest regions on Earth, located in the tropics, where changes in the tails of the temperature distribution have emerged first

It is found that human-caused increases in heat waves have depressed economic output most in the poor tropical regions least culpable for warming.

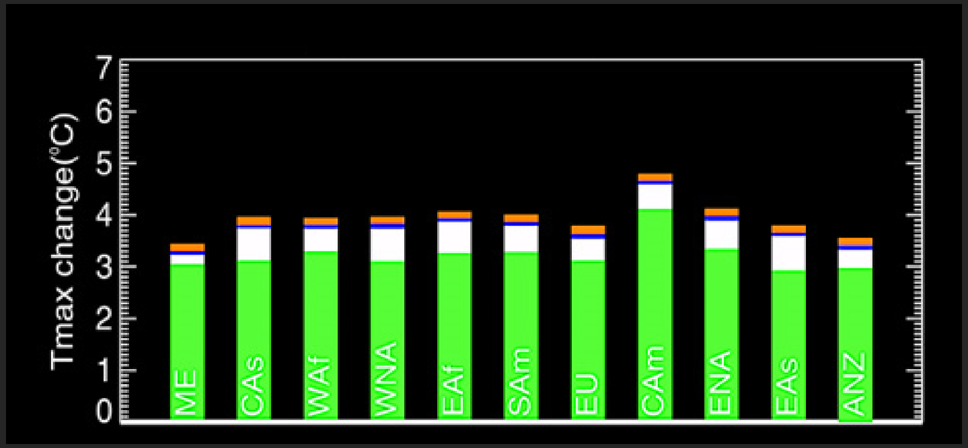
Cumulative 1992–2013 losses from anthropogenic extreme heat likely fall between $16 trillion and $50 trillion globally. Losses amount to 8% of Gross Domestic Product per capita per year for regions in the bottom income decile, but only 3.5% for regions in the top income decile.

Callahan et al: Globally unequal effect of extreme heat on economic growth, Science Advances, 2023

Potential Increase of Min Nighttime Temperature (C)



Potential Increase of Max Daytime Temperature (C)

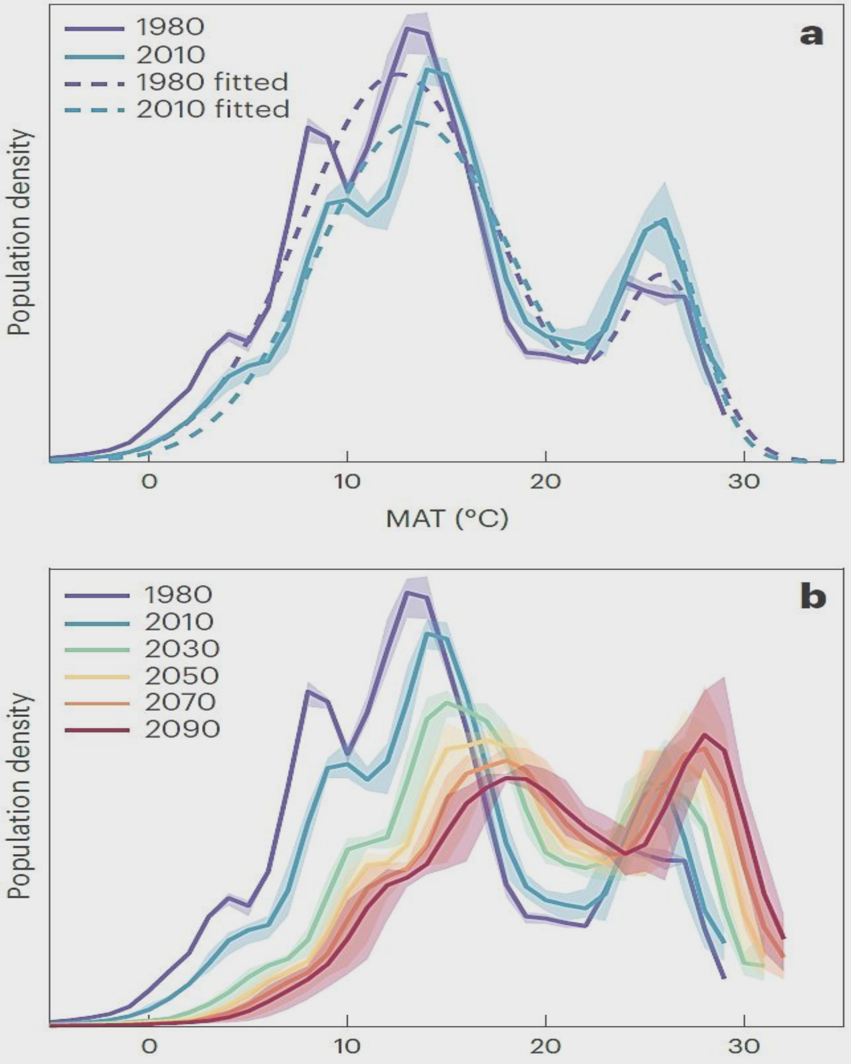


Simulated Increase of the Urban Temperature and UHI caused by the combined impact of greenhouse gas and urban expansion forcing, (RCP 8.5)

- Increase in the Surrounding Rural zone (2 x CO_2)
- Increase in the City (2 x CO_2)
- Increase in the City (2 x CO_2)+ 20 w/m2 anthropogenic heat
- Increase in the City (2 x CO_2)+ 60 w/m2 anthropogenic heat

Middle East (ME), Central Asia (CAs), West Africa (WAf)
West North America (WNA), East Africa (EAf), South America (SAm),
Europe (EU), Central America (CAm), East North America (ENA),
Australia and New Zealand (ANZ)

Climate change in cities due to global warming and urban effects. Mark P. McCarthy, Martin J. Best, and Richard A. Betts, GEOPHYSICAL RESEARCH LETTERS, VOL. 37, L09705



MAT : Mean Annual Temperature

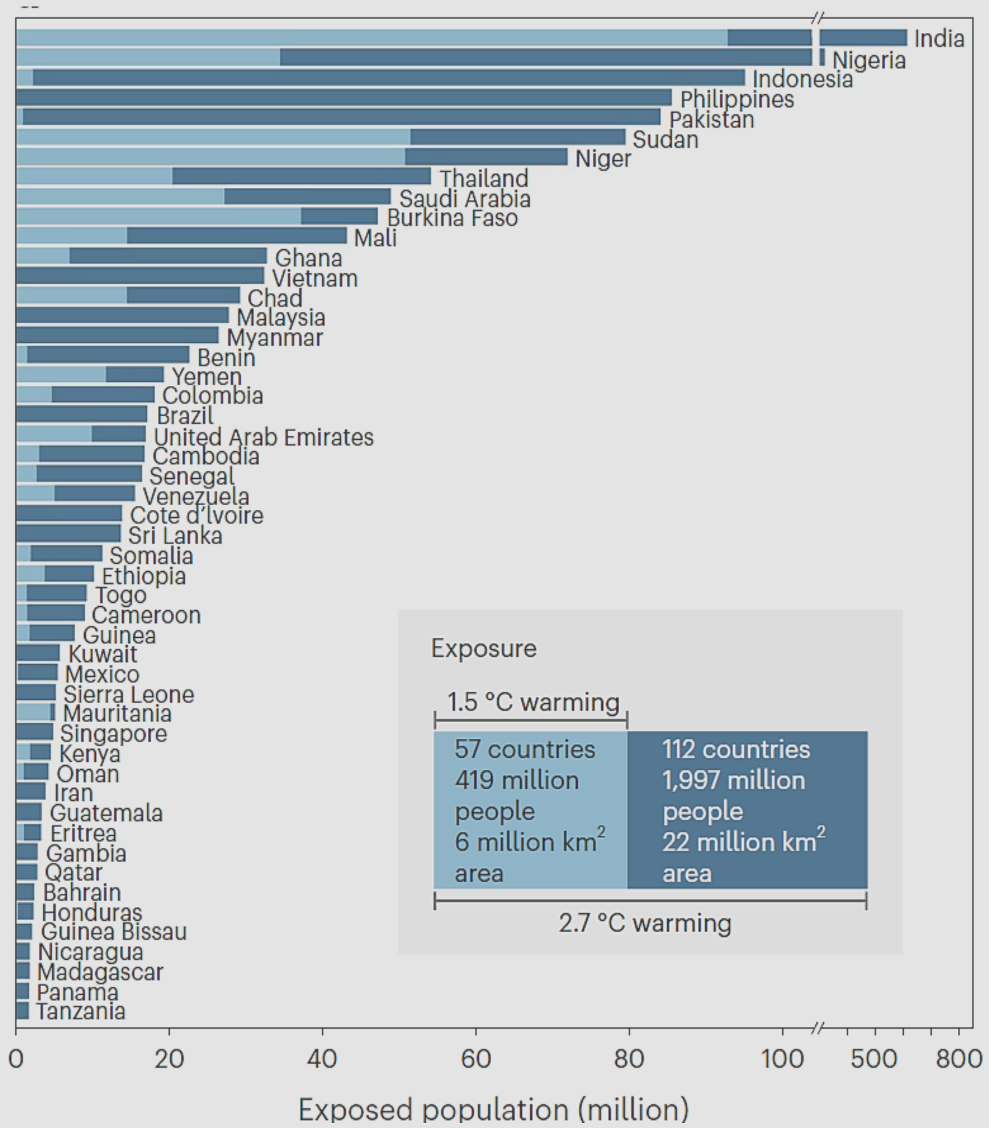
The ‘human climate niche’ is defined as the historically highly conserved distribution of relative human population density with respect to mean annual temperature.

Climate change has already put ~9% of people (>600 million) outside this niche

By end-of-century (2080–2100), current policies leading to around 2.7 °C global warming could leave one-third (22–39%) of people outside the niche

This population comes from a place where emissions today are around half of the global average

Timothy M. Lenton , Chi Xu, Jesse F. Abrams, Ashish Ghadiali, Sina Loriani, Boris Sakschewski, Caroline Zimm, Kristie L. Ebi, Robert R. Dunn, Jens-Christian Svenning & Marten Scheffer: Quantifying the human cost of global warming, Nature Sustainability, 2023



The 'human climate niche' is defined as the historically highly conserved distribution of relative human population density with respect to mean annual temperature.

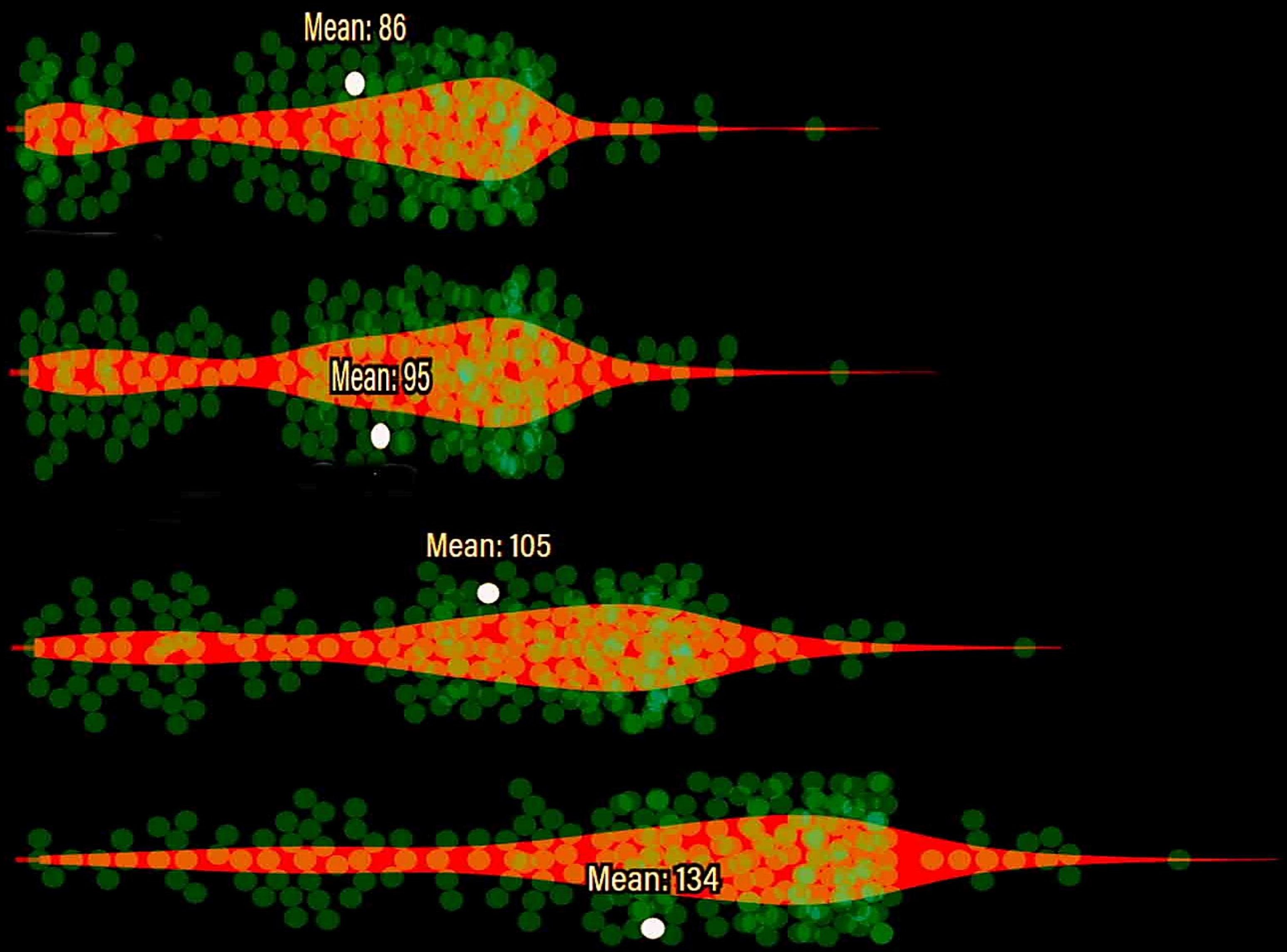
Climate change has already put ~9% of people (>600 million) outside this niche

Country-level exposure to unprecedented heat (MAT ≥29 °C) at 2.7 °C and 1.5 °C global warming in a world of 9.5 billion people (around 2070 under SSP2).

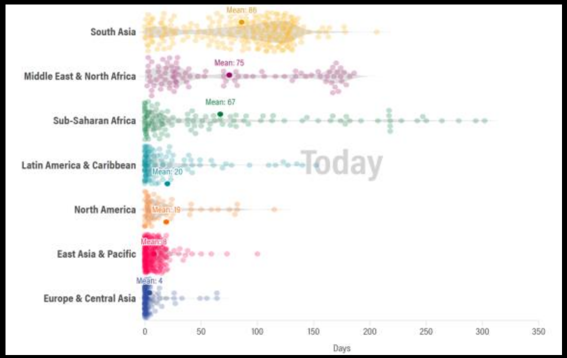
Population exposed for the top 50 countries ranked under 2.7 °C global warming (dark blue) with exposure at 1.5 °C global warming overlaid (pale blue).

Timothy M. Lenton , Chi Xu, Jesse F. Abrams, Ashish Ghadiali, Sina Loriani, Boris Sakschewski, Caroline Zimm, Kristie L. Ebi, Robert R. Dunn, Jens-Christian Svenning & Marten Scheffer: Quantifying the human cost of global warming, Nature Sustainability, 2023

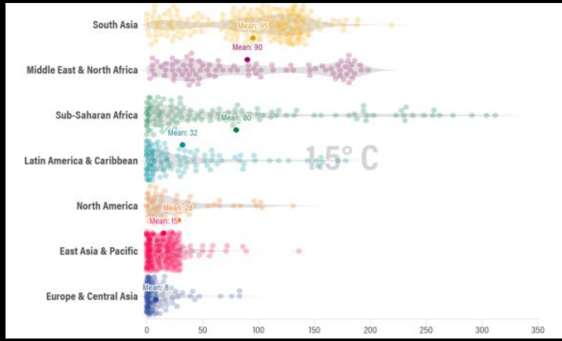
Days per Year that Max Temperature Exceeds 35 C by City in Southeast Asia



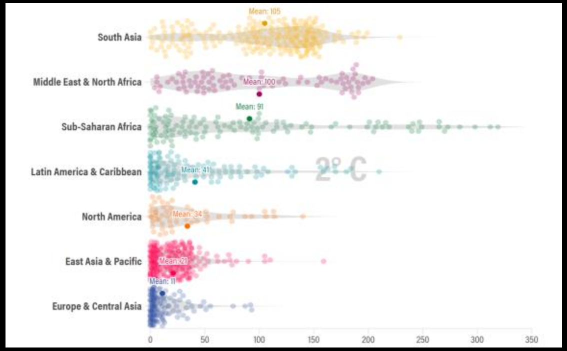
Current



+ 1.5 C



+ 2.0 C

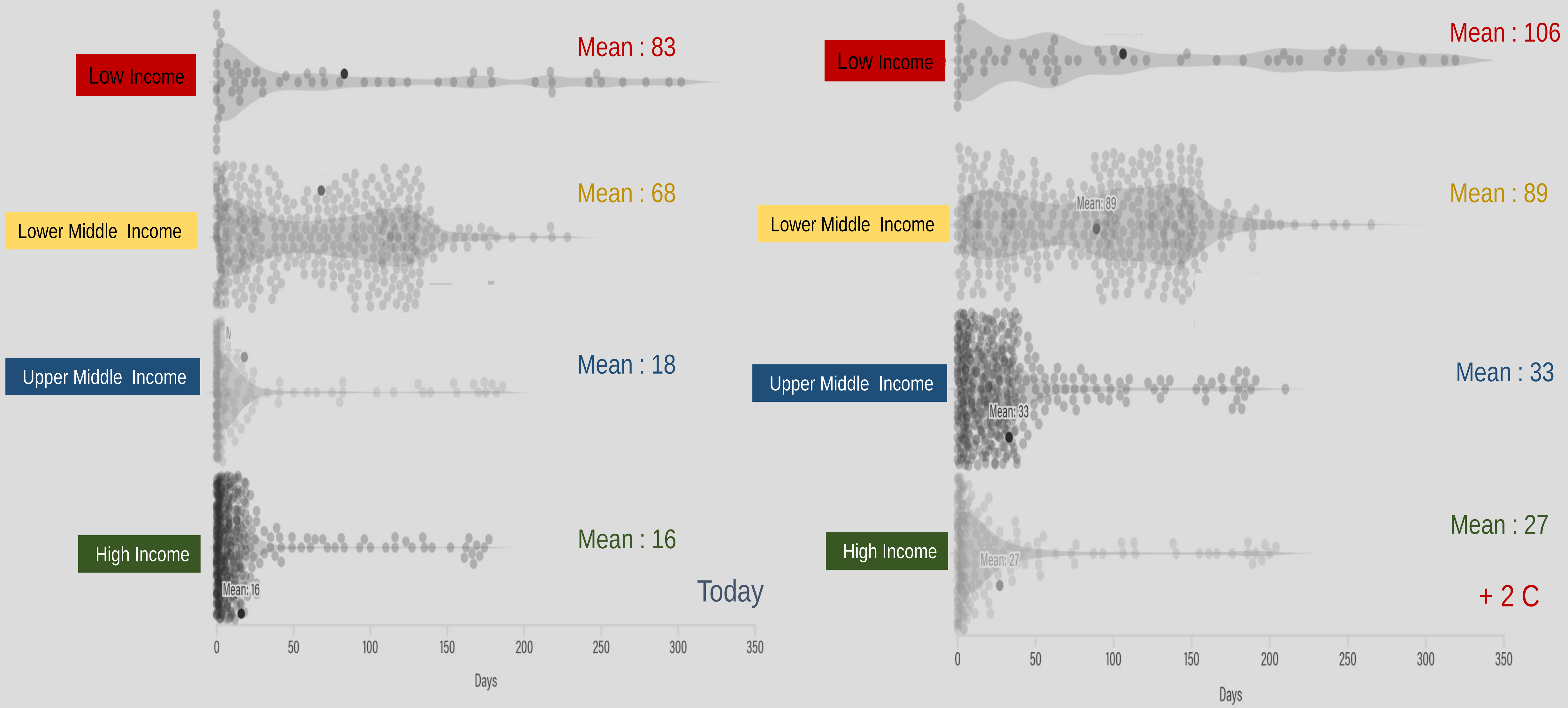


+ 3.0 C

Source: WRI analysis from IPCC Interactive Atlas, Bias Adjusted TX35 from CMIP6.

WORLD RESOURCES INSTITUTE

Days per Year that Max Temperature Exceeds 35 C by City



Source: WRI analysis from IPCC Interactive Atlas, Bias Adjusted TX35 from CMIP6.

WORLD RESOURCES INSTITUTE

There currently is a shortfall of about 330 million homes in the world, and is expected to increase up to 440 million by 2025.

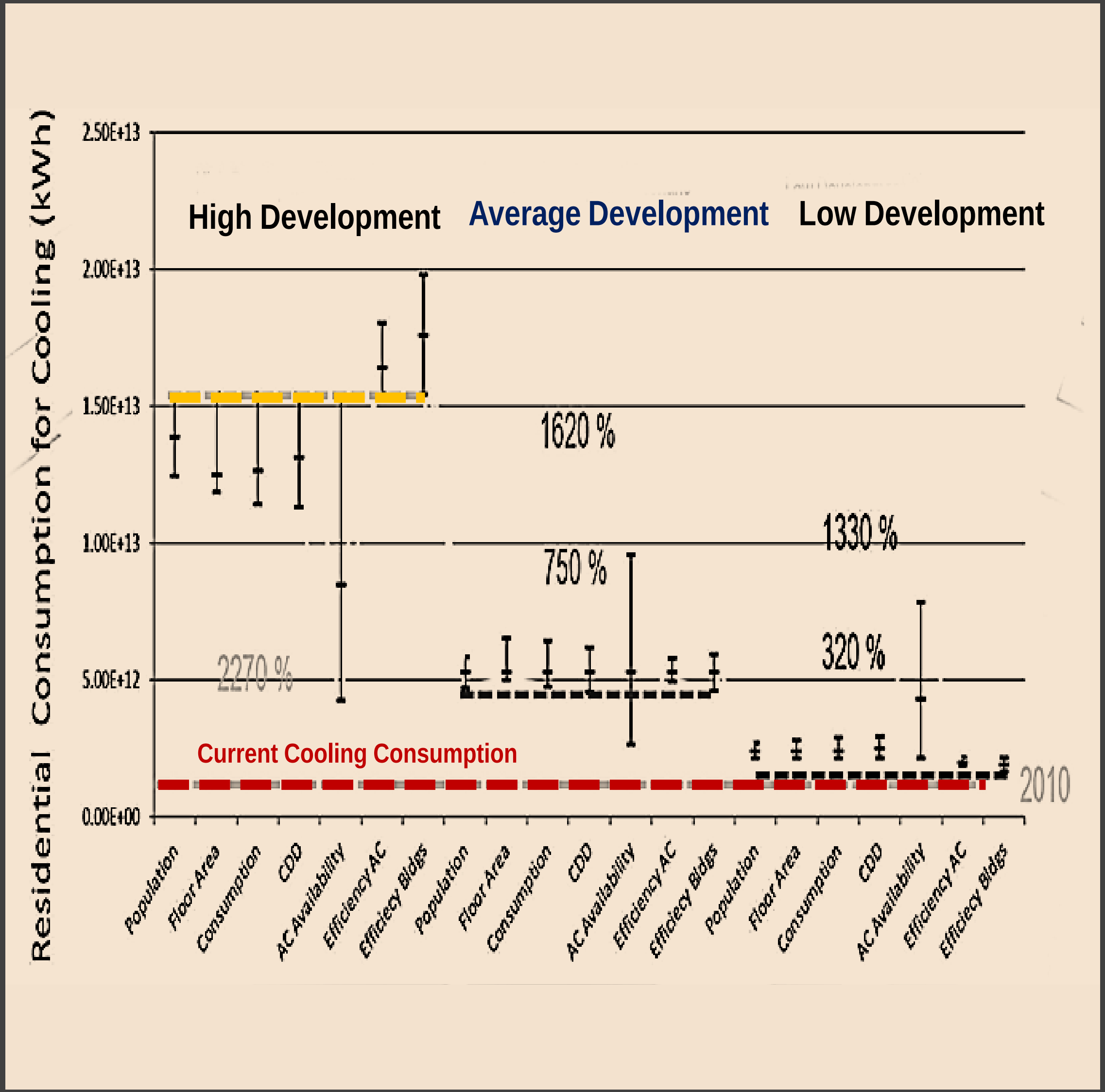
.

By 2030 the additional housing needs will grow by more than 77 billion square meters of floor space, equivalent or greater than the actual area of China

More than **225 billion square meters** of floor area will be built in emerging economies and mainly in India, Indonesia and Brazil

We add a total floor area equal to the city of Paris per week.

M. Santamouris : Minimizing Energy Consumption, Energy Poverty and Global and Local Climate Change in the Built Environment: Innovating to Zero, Causalities and Impacts in a Zero Concept World, Elsevier, 2019



Cooling Energy Consumption of Buildings by 2050

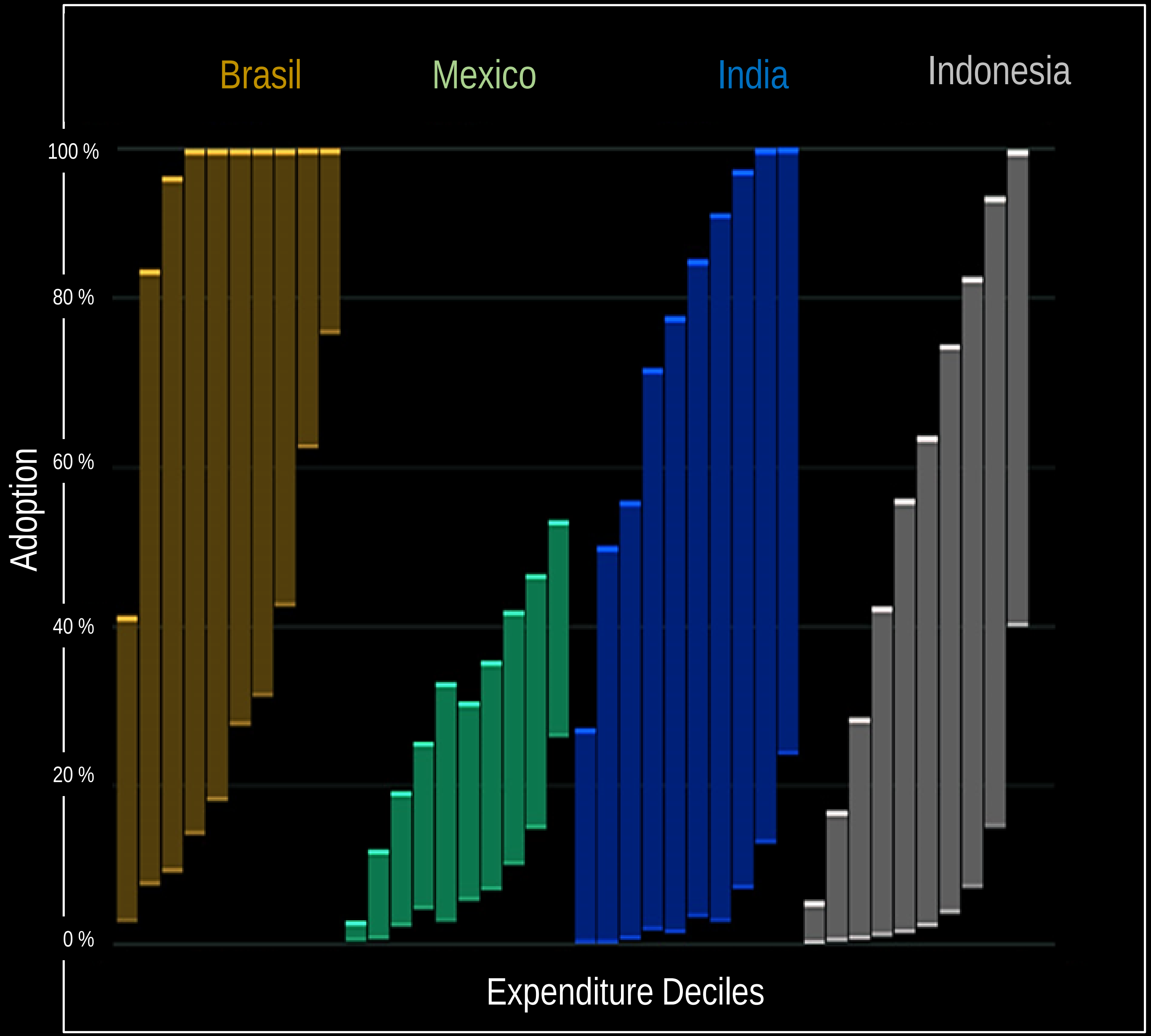
Data shows that extreme heat drives higher air conditioner demand, with sustained average daily temperatures of 30 C typically boosting weekly sales by around 16 %.

Cooling energy consumption in buildings may rise by 200% and up to 2,000% by 2050, depending on the evolution of the main economic and climatic drivers.

.

The total cost of urban overheating is estimated between 500 – 700 billion US $ per year, and may increase up to 1.3 Trillion US $ by 2050

M. Santamouris : Cooling of Buildings. Past, Present and Future, Energy and Buildings, 128 (2016)

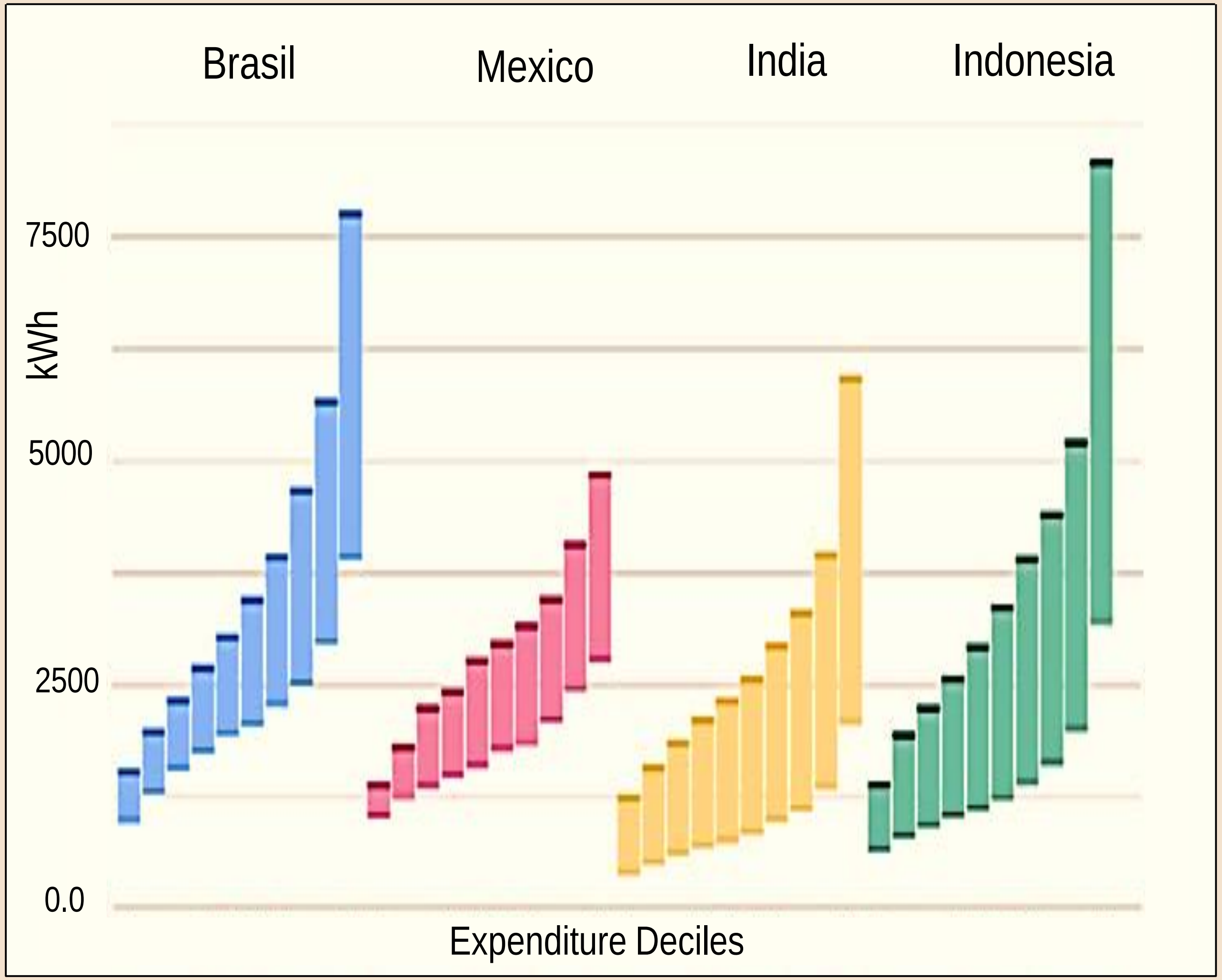


The Current and Future Penetration of A/C in Emerging Economies per Income Group demonstrates that low income population will not have access to air conditioning.

By 2040, a nonnegligible fraction of the population will be left behind.

In 2040, between 64 and 100 million households out of the total number of households living in the four countries considered in the latest waves of 343 million will face an adaptation cooling deficit

NATURE COMMUNICATIONS | (2021) 12:6460 | https://doi.org/10.1038/s41467-021-26592-2 | www.nature.com/naturecommunications

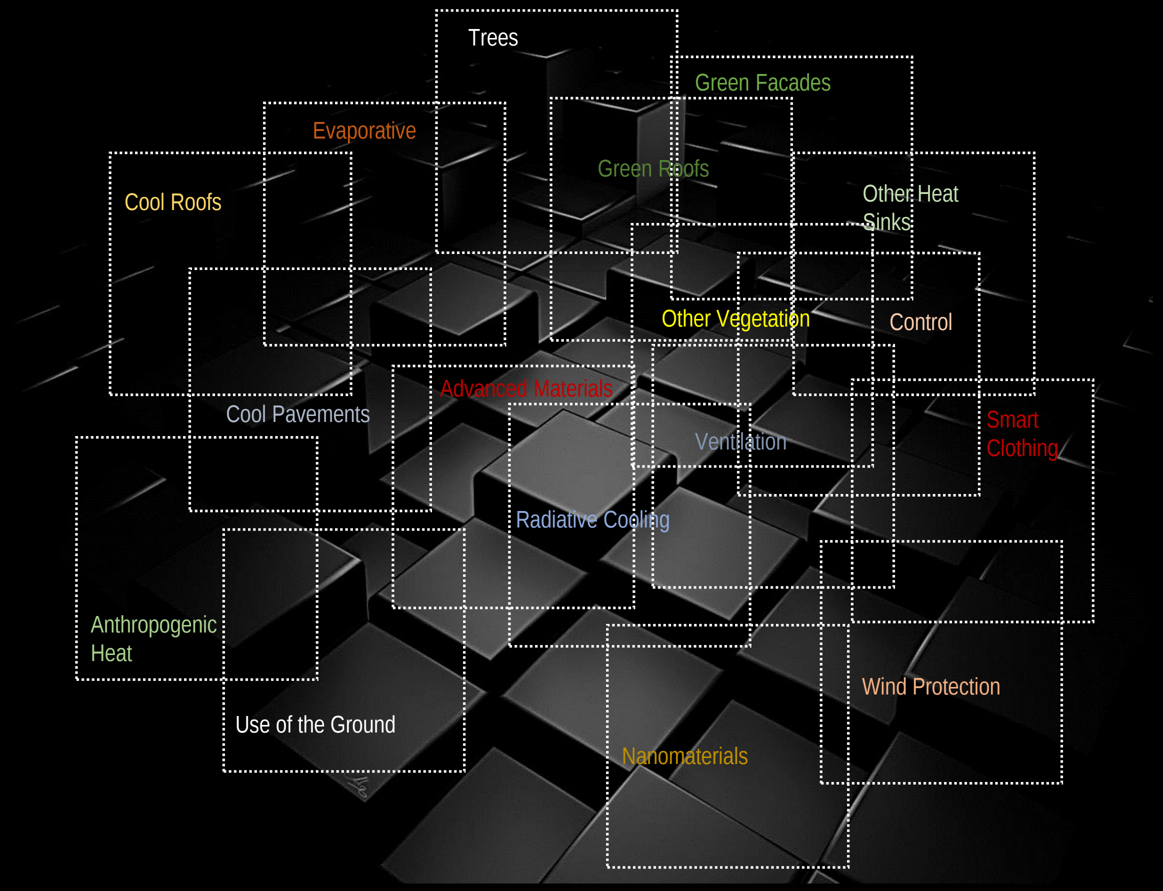


The Current and Future Cooling Energy Consumption in Emerging Economies per Income Group differs and will continue to differ significantly.

Low Income population is covering and will continue to cover a very small or even negligible part of their cooling requirements

As a result, low income population will continue to live under unacceptable indoor environmental conditions while high indoor temperatures will consist a very serious threat for their health and well being.

NATURE COMMUNICATIONS | (2021) 12:6460 | https://doi.org/10.1038/s41467-021-26592-2 | www.nature.com/naturecommunications



To counterbalance the impact of urban overheating, heat mitigation techniques are developed, and successfully implemented.

Mitigation technologies involve the use of advanced urban materials like:

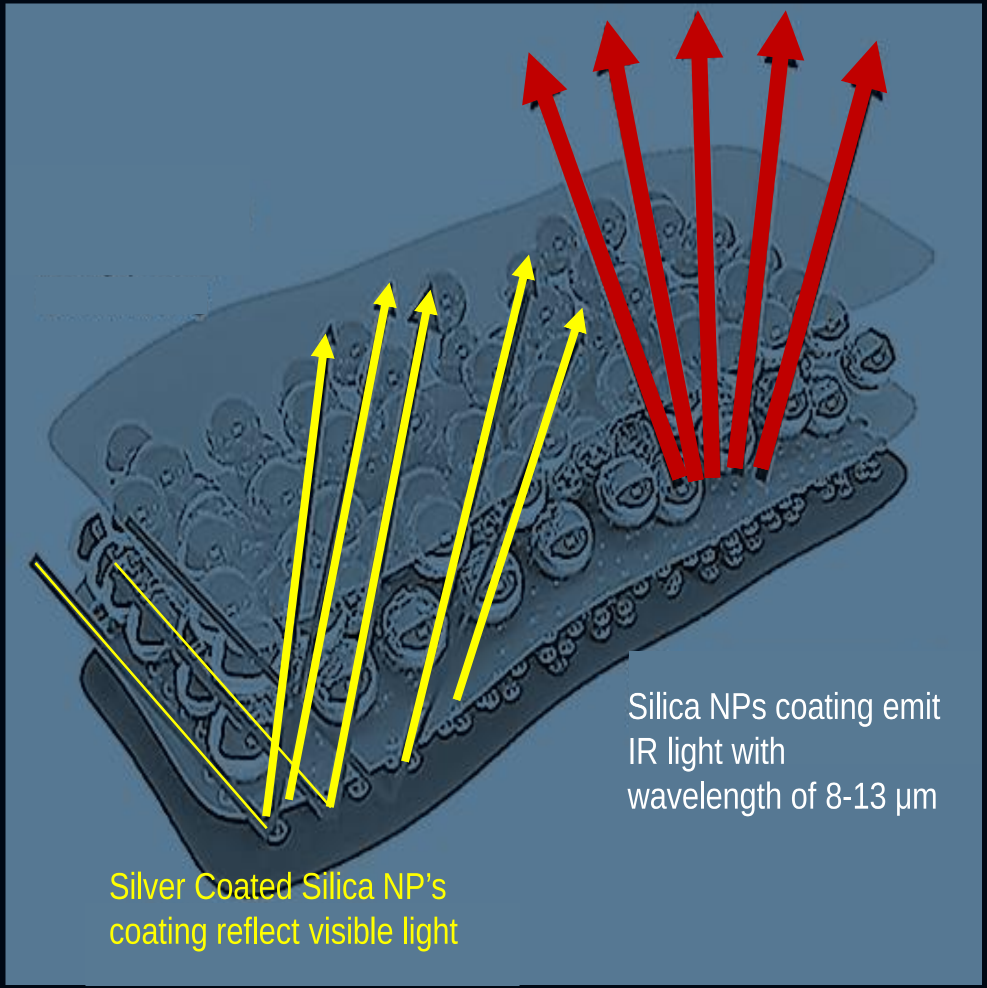
Reflective, thermochromic, photonic, plasmonic and fluorescent materials,

The increase of the urban green infrastructure,

The use of evaporative systems,

Dissipation of the excess urban heat to low temperature heat sinks,

Or, a combination of the previous technologies.



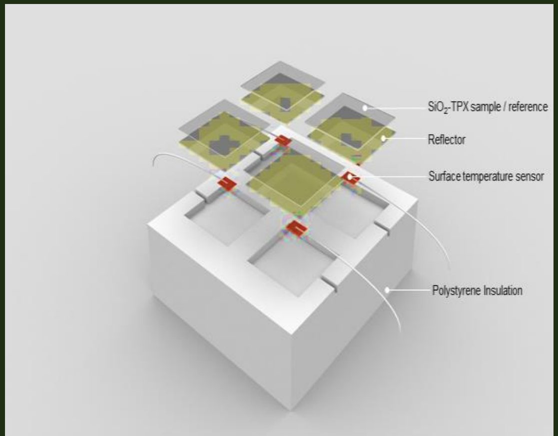
Passive Radiative Coolers, or Super Cool Materials, present a very high solar absorptance combined with a high emissivity in the atmospheric window, 7-13 μm.

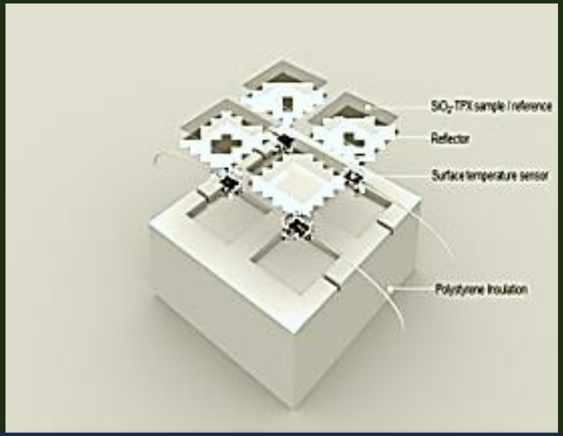
The recent development of

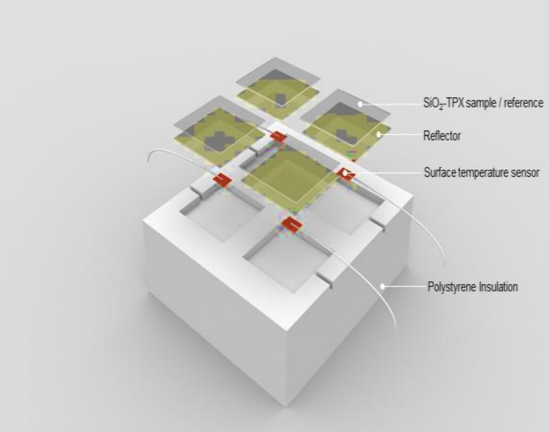
Super Cool Materials

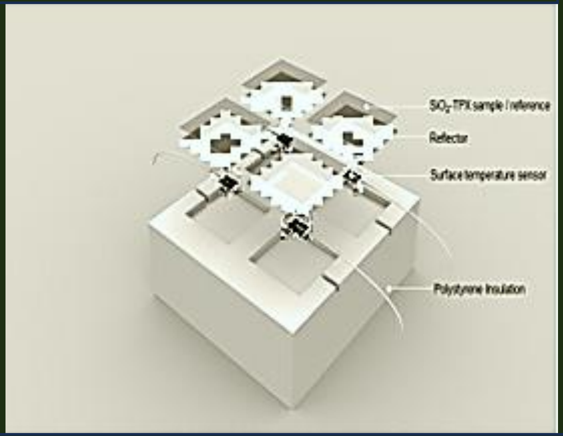
like the photonic and fluorescent materials, permits the decrease of the surface temperature of buildings and urban structures up to 15 C below the ambient temperature under the summer sun

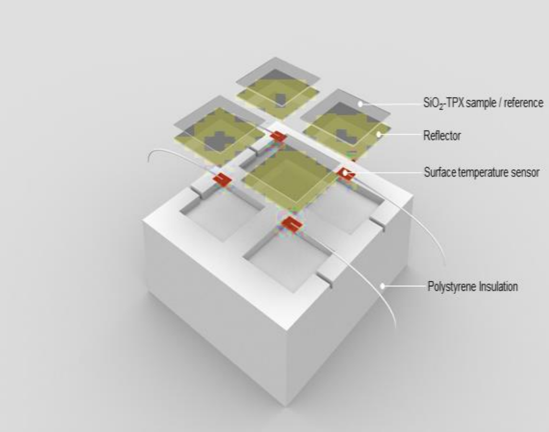
The implementation of SCM in cities can reduce the peak ambient temperature up to 4-5 C and provide very significant energy and health benefits.

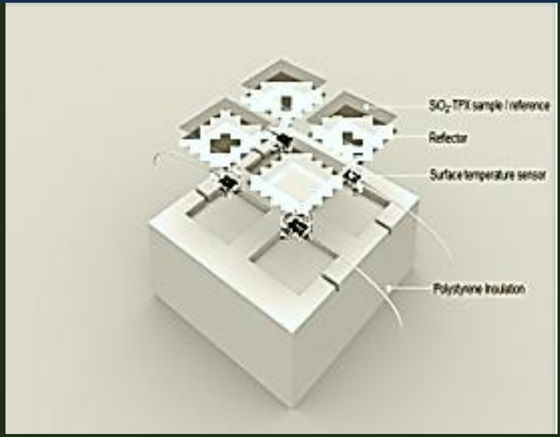












TPX Polymethylpentene (PMP) is a lightweight, functional polymer with a unique combination of transparency, heat and chemical resistant properties

We optimized the influence of the silica sphere’s radius, sphere volume fraction, and silica-TPX layer thickness on the material’s optical properties and cooling efficiency using theoretical predictions, (FDTD

Jie Feng, Kai Gao, M. Santamouris, K.W. Shah and G. Ranzi : Dynamic Impact of Climate on the Performance of Daytime Radiative Cooling Materials, Solar Energy Materials and Solar Cells, Volume 208, May 2020, 110426
Jie Feng, M. Santamouris and K. Gao :The Radiative Cooling Efficiency of Silica Sphere Embedded Polymethylpentene (TPX) Systems, Solar Energy Materials and Solar Cells, , Volume 215, 15 September 2020, 110671
Jie Feng , A, Khan and M, Santamouris : The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale Cell Reports Physical Science, 100485 July 21, 2021
Feng J Kai Gao Yue Jiang Giulia Ulpiani Djordje Krajcic Riccardo Paolini Gianluca Ranzi and M. Santamouris : Optimization of Random Silica-Polymethylpentene (TPX) Radiative Coolers Towards Substantial Cooling CapacitySolar Energy Materials and Solar Cells Volume 234, January 2022, 11141

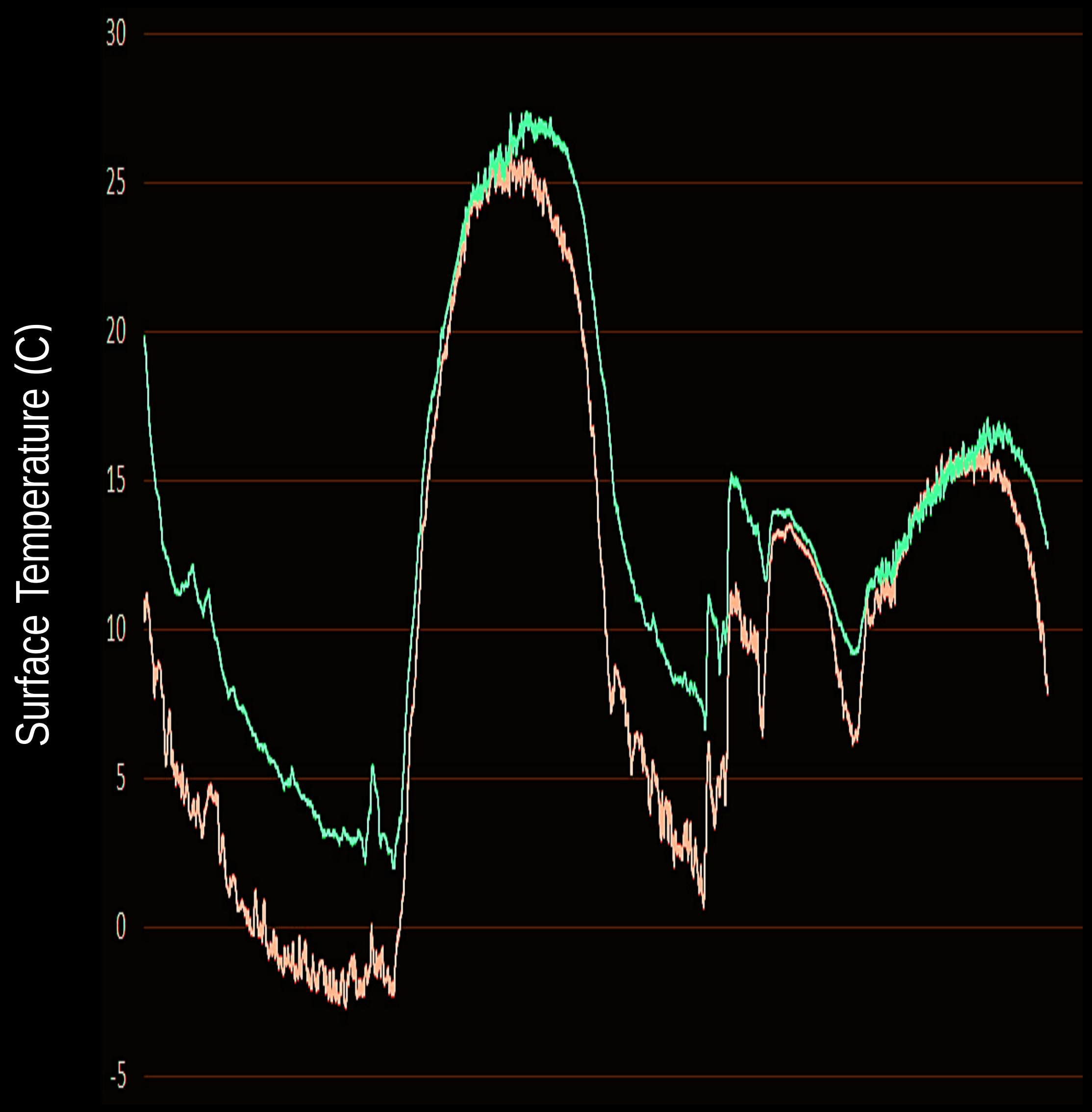
The developed samples of the Super Cool Materials have been extensively tested outdoors in Alice Springs, Australia, under desert conditions, to characterize their cooling performance.

Six Samples with Different Characteristics have been designed.

The microstructure of the samples was analyzed by field emission SEM (FESEM; FEI Nova NanoSEM 230, 3 kV) and their element composition was studied by EDS - Energy Dispersive Spectrometry).

Desert climatic conditions permit testing under high day time ambient temperature and solar radiation intensity.

However, the desert atmosphere contains a high concentration of SiO_2 that is highly absorbing in the atmospheric window, thus decreasing the cooling performance of the materials.



Testing has been carried out during several days in Alice Springs, Australian Desert.

Max Day time ambient temperature was 27.5 C

The peak solar Radiation intensity was between 740 W/m2

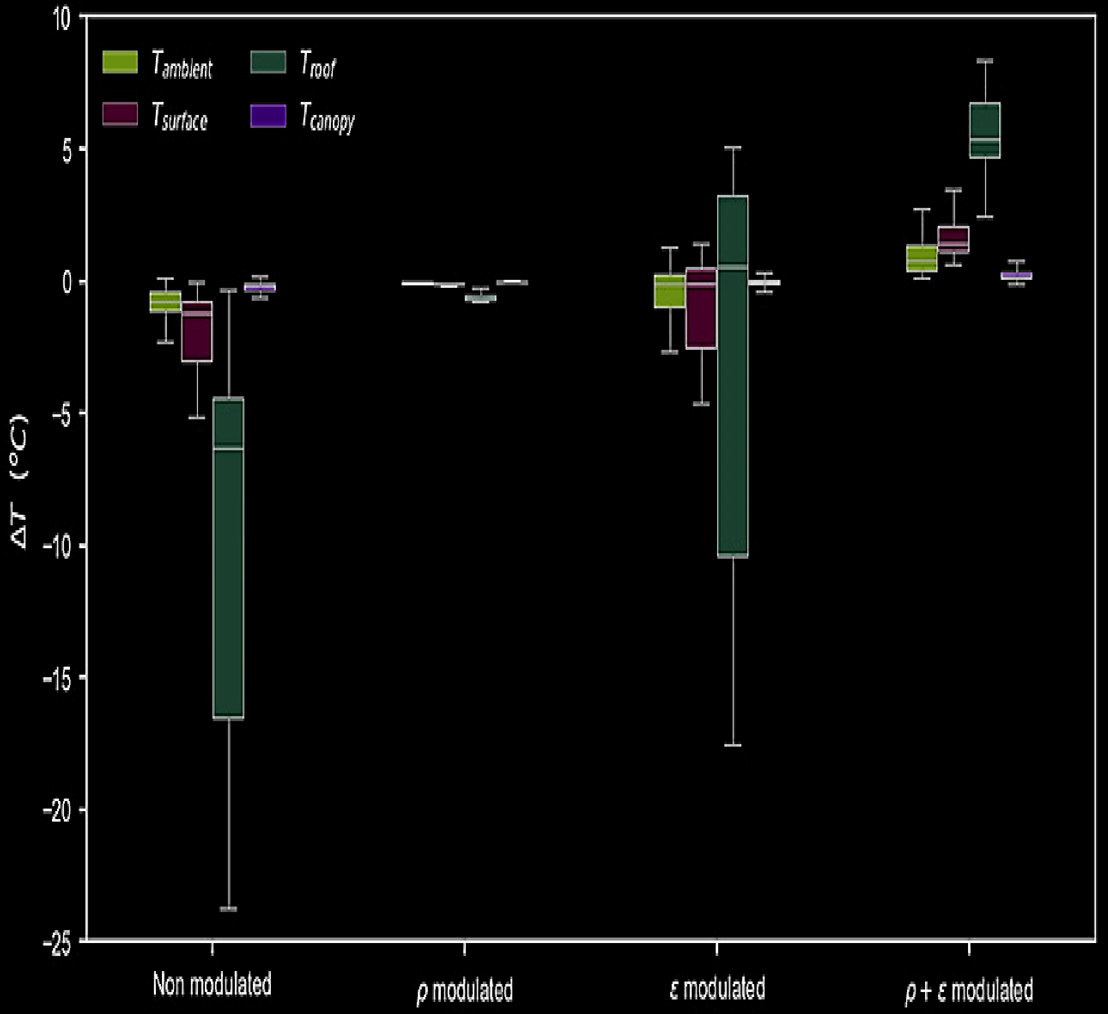
Relative Humidity at Noon Time : 20 %

During the Day Time:

The Surface temperature of the developed Super Cool Paint was in average 1.8 C lower than the ambient one. During the peak daytime period sub-ambient cooling was close to 1.4 C

During the Night Time:

The Surface temperature of the SCM was almost 8 C lower than the ambient one.



Because of their high solar reflectance and the white or metal color, PDRC materials cause undesired aesthetic and visual problems and can be used only on high level roofs, while may increase the heating energy demand of buildings in temperate and continental climates

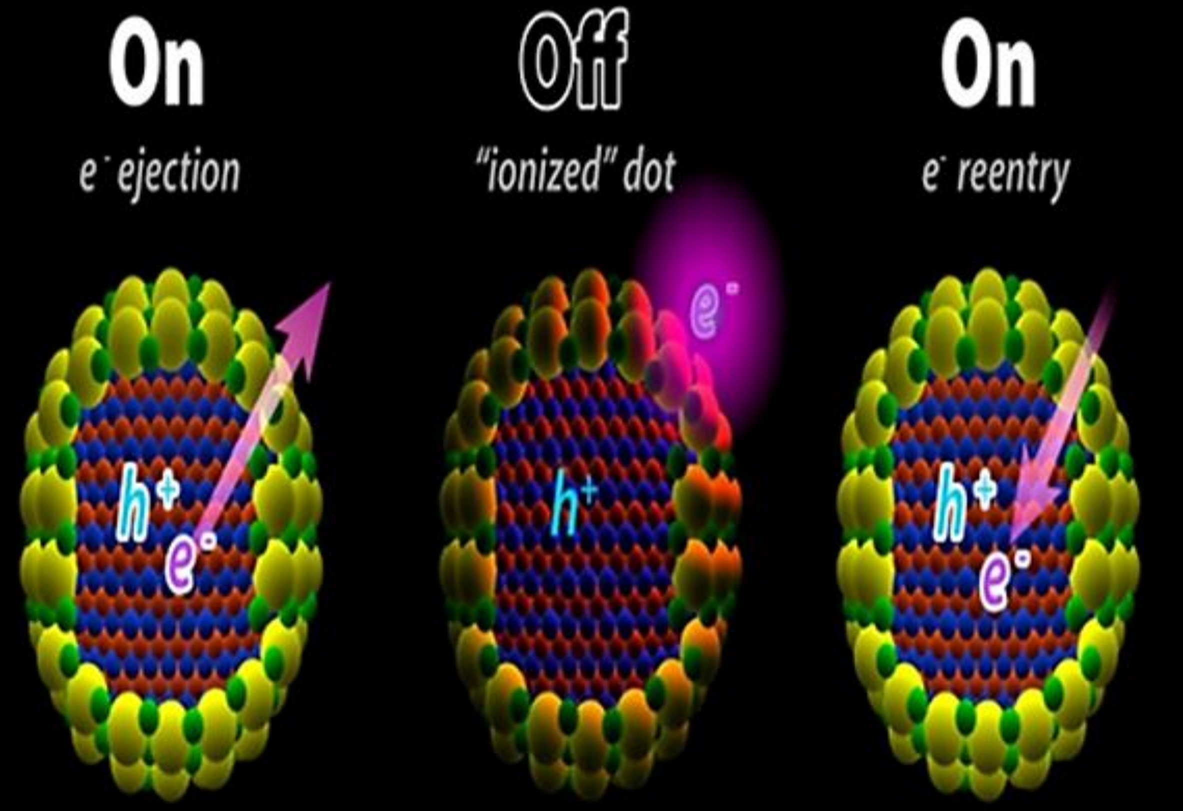
Modulation of the Reflectance and Emissivity of the PDRC's offers important energy benefits during both the Cooling and Heating period.

Use of SCM may decrease the ambient temperature up to 2 C

Results of WRF simulations for Kolkata India

Ansar Khan, Laura Carlosena, Jie Feng, Samiran Khorat, Rupali Khatun, Quang-Van Doan, Mattheos Santamouris : Optically modulated passive broadband daytime radiative cooling materials can cool cities in summer and heat cities in winter, Sustainability, 2022, 14, 1110

Ansar Khan, Laura Carlosena, Samiran Khorat, Rupali Khatun Quang-Van Doan, Jie Feng, Mattheos Santamouris On the Winter Overcooling Penalty of Super Cool Photonic Materials in Cities, Advances Solar Energy Vol 1, 2021



Passive Colored Radiative Coolers, PCRC, based on the use of fluorescent materials, convert part of the absorbed UV and visible solar radiation into emitted light, providing color and reducing the thermal balance of the materials and the potential visual annoyance

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.

Samira Garshasbi , Shujuan Huang , Jan Valenta , Mat Santamouris : On the combination of quantum dots with near-infrared reflective base coats to maximize their urban overheating mitigation potential, Solar Energy, Volume 211, 15 November 2020, Pages 111-116

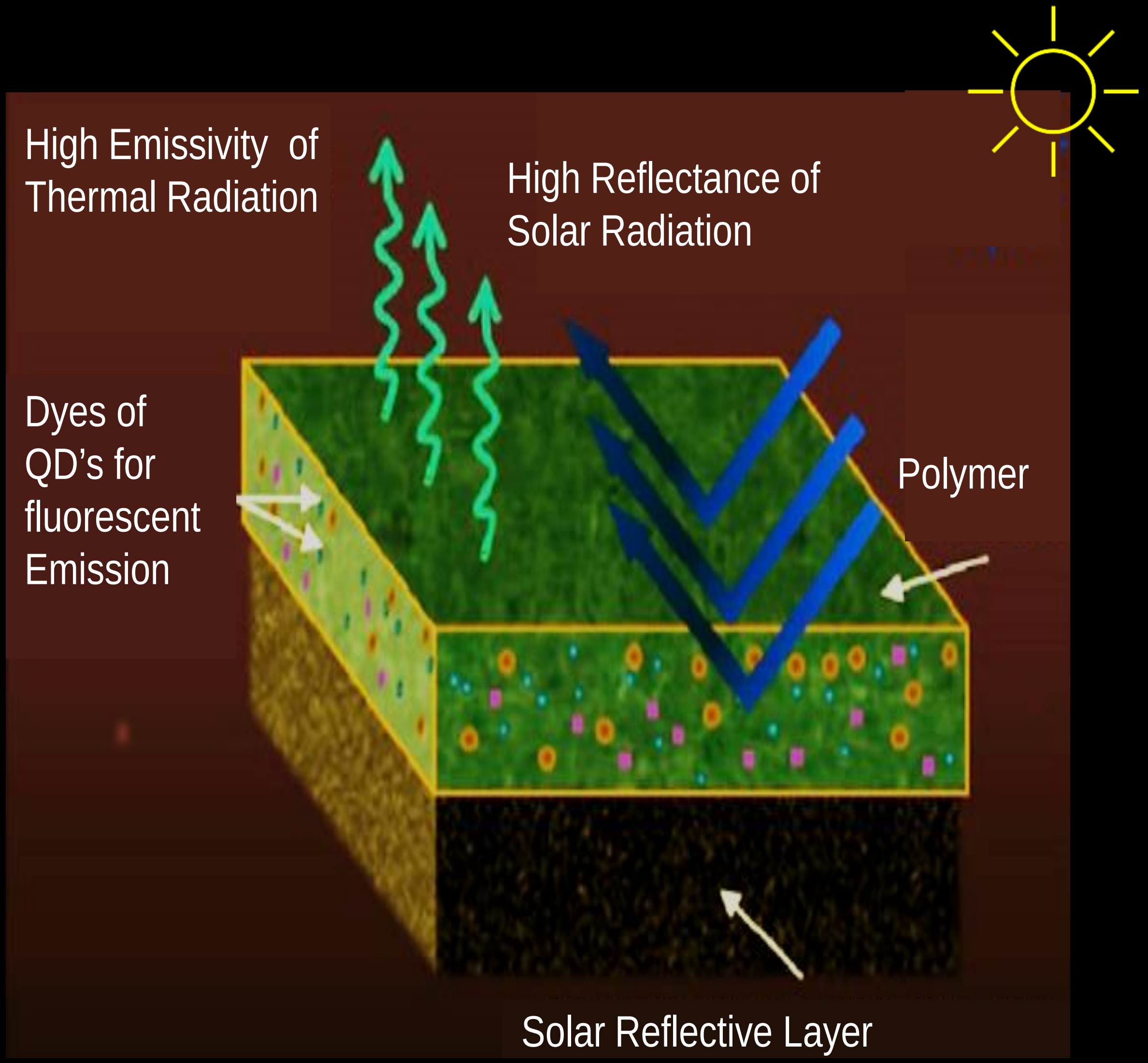


Figure idea :Colored radiative cooling coatings using phosphor dyes : J. Xu, R. Wan, W. Xu, Z. Ma, X. Cheng, R. Yang, X. Yin

Colored Radiative Coolers based on the use of fluorescent materials have been developed and tested.

Materials were designed in order to present:

- High Reflectance to Solar Radiation
- High Emissivity in the Atmospheric window, and
- High radiative losses because of the fluorescent emission

The developed colored radiative coolers were composed by two or three specific layers:

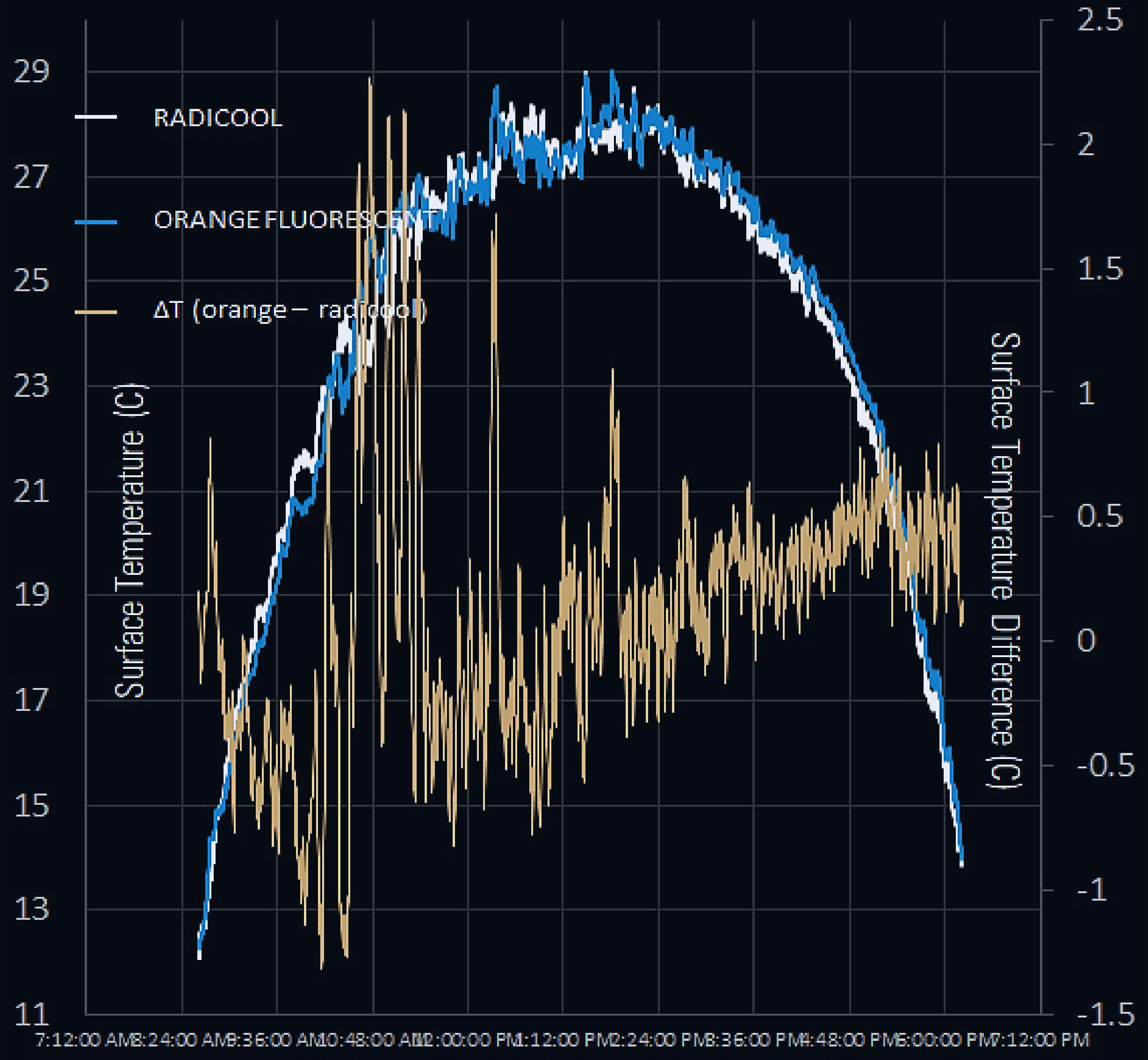
- A reflective layer, and
- A high emissivity and/or a high PLQY layer on the top to provide fluorescent emission at various colors and also high emissivity in the atmospheric window

All developed materials have been tested extensively during the summer of 2023 in Alice Springs, in the Australian desert.

Climatic Conditions

Maximum Daytime Ambient Temperature : 27.5 C
Maximum Daytime Rel Humidity : 50 %
Minimum Daytime Rel Humidity : 20 %
Average Daytime Wind Speed : 1.4 m/sec
Maximum Daytime Wind Speed : 7.2 m/sec

Maximum Solar Radiation : 750 W/m2
Average Daytime Long Wave Radiation : 300 W/m2



25/5/2023 – Alice Springs- Orange Fluorescent SC Material

Max Amb. Temp : 27.4 C

Max SR : 740 W/m2

RH (noon) : 20 %,

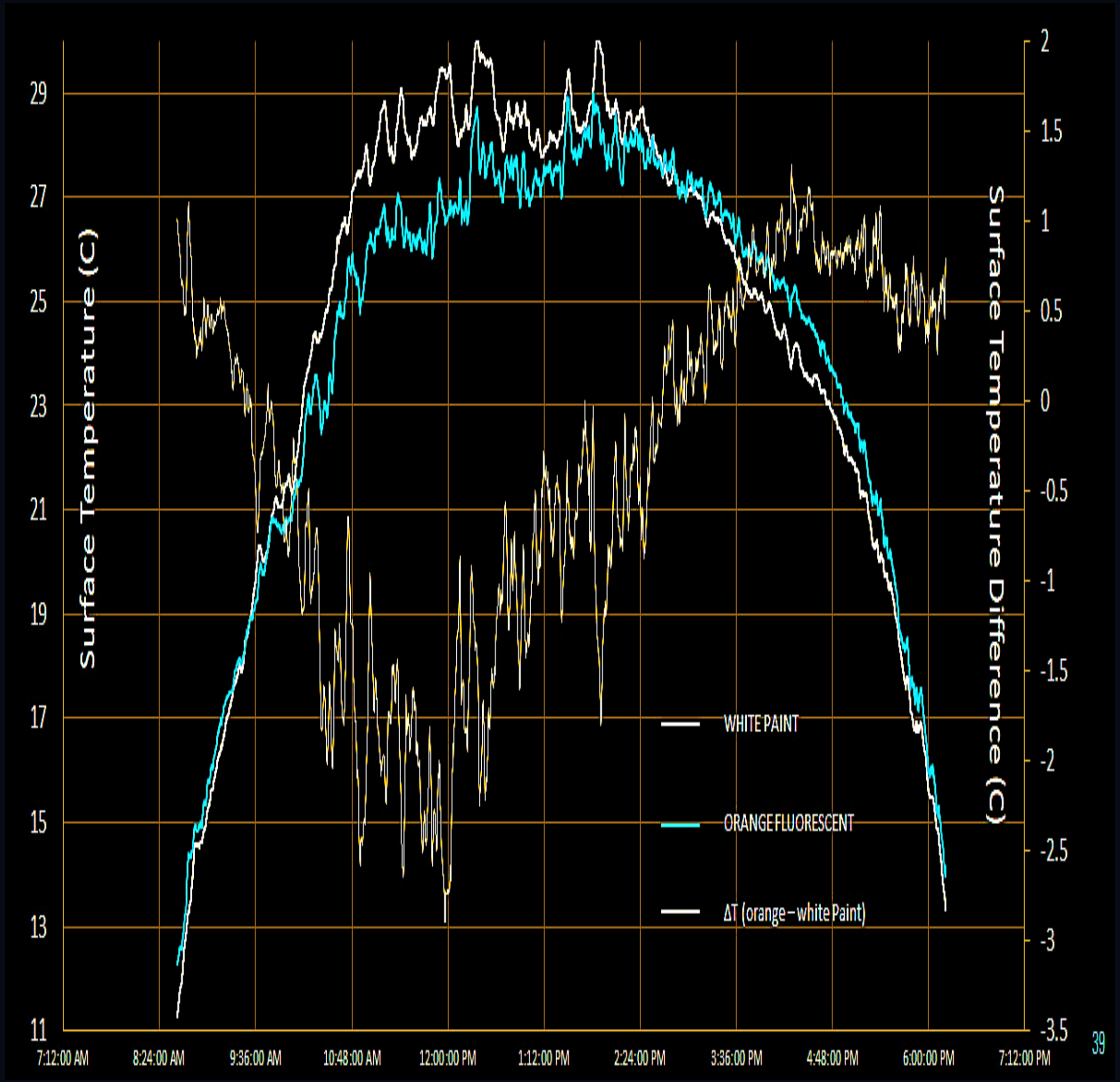
Max Atm Rad : 370 W/m2

Comparison of the Orange Colored SCM against the White SCM

During the day time the average temperature of the white SCM was 24 C

while of the Orange SCM was 24.1 C

The orange Super Cool material exhibited during the day time period up to 1.5 C sub-ambient temperature.



25/5/2023 – Alice Springs- Orange Fluorescent SC Material against conventional white paint.

Max Amb. Temp : 27.4 C

Max SR : 740 W/m2

RH (noon) : 20 %,

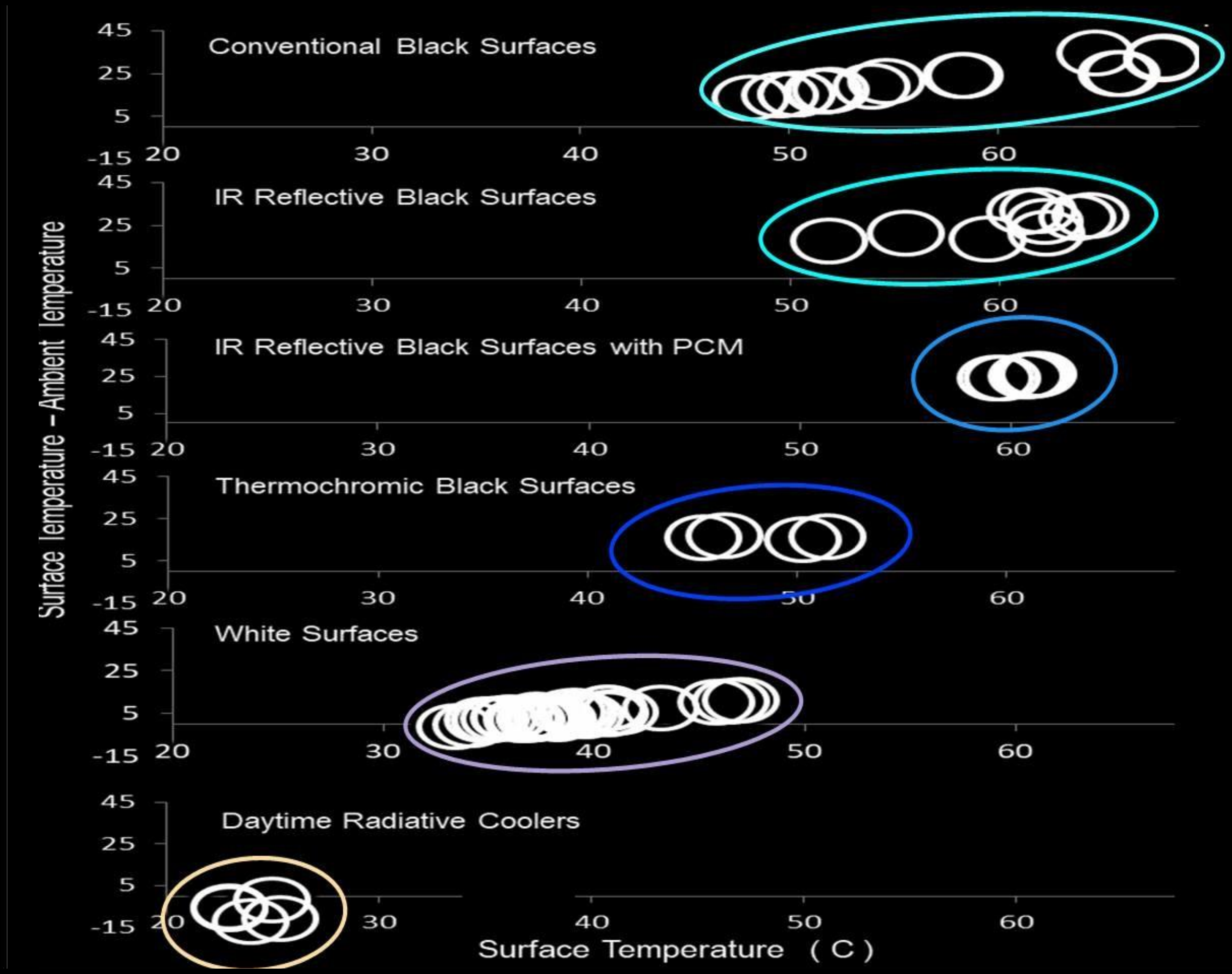
Max Atm Rad : 370 W/m2

Comparison of the Colored against Conventional White Paint

During day time the average temperature of the white paint was 24.6 C

while of the Orange SCM was 24.1 C

During noon time the orange Super Cool material was almost 3 C of lower surface temperature than the white paint.

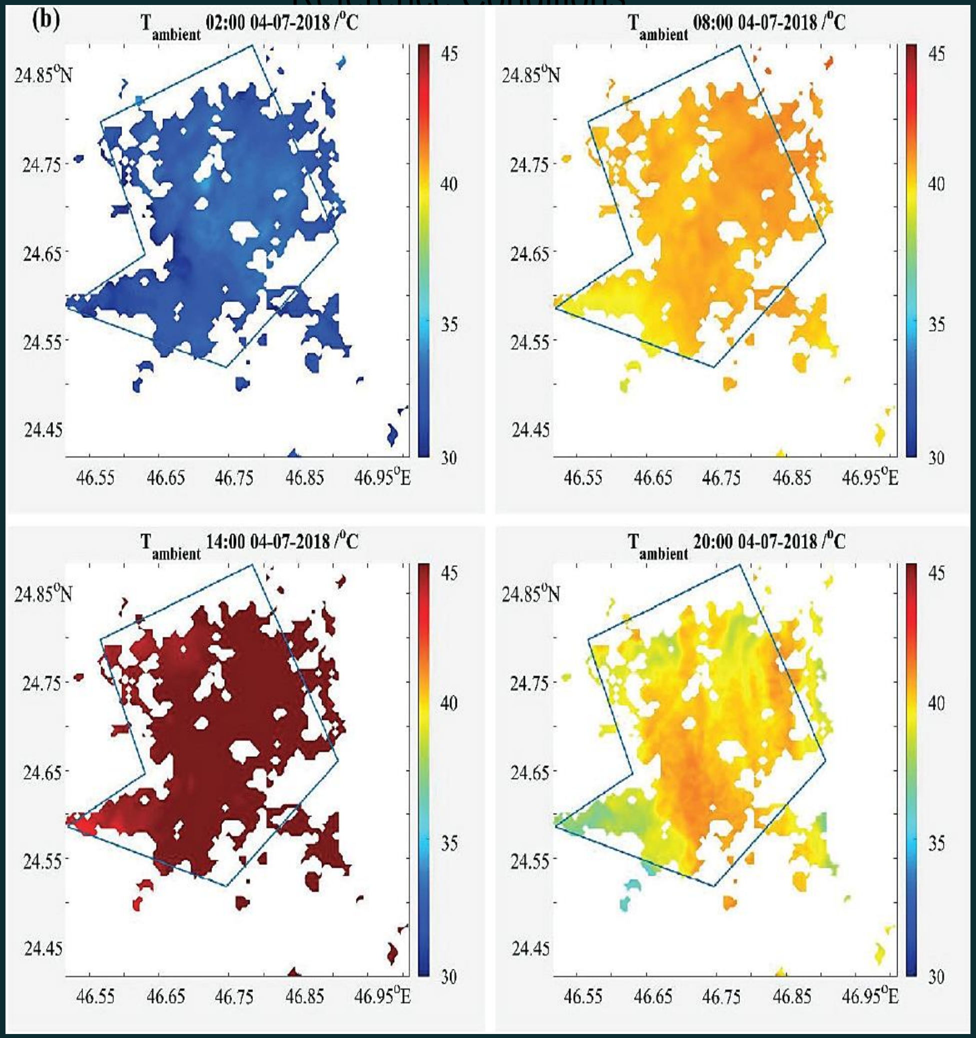


Comparative outdoor assessment of the main types of coatings for the built environment carried out under similar climatic conditions demonstrated the important progress in terms of cooling mitigation potential.

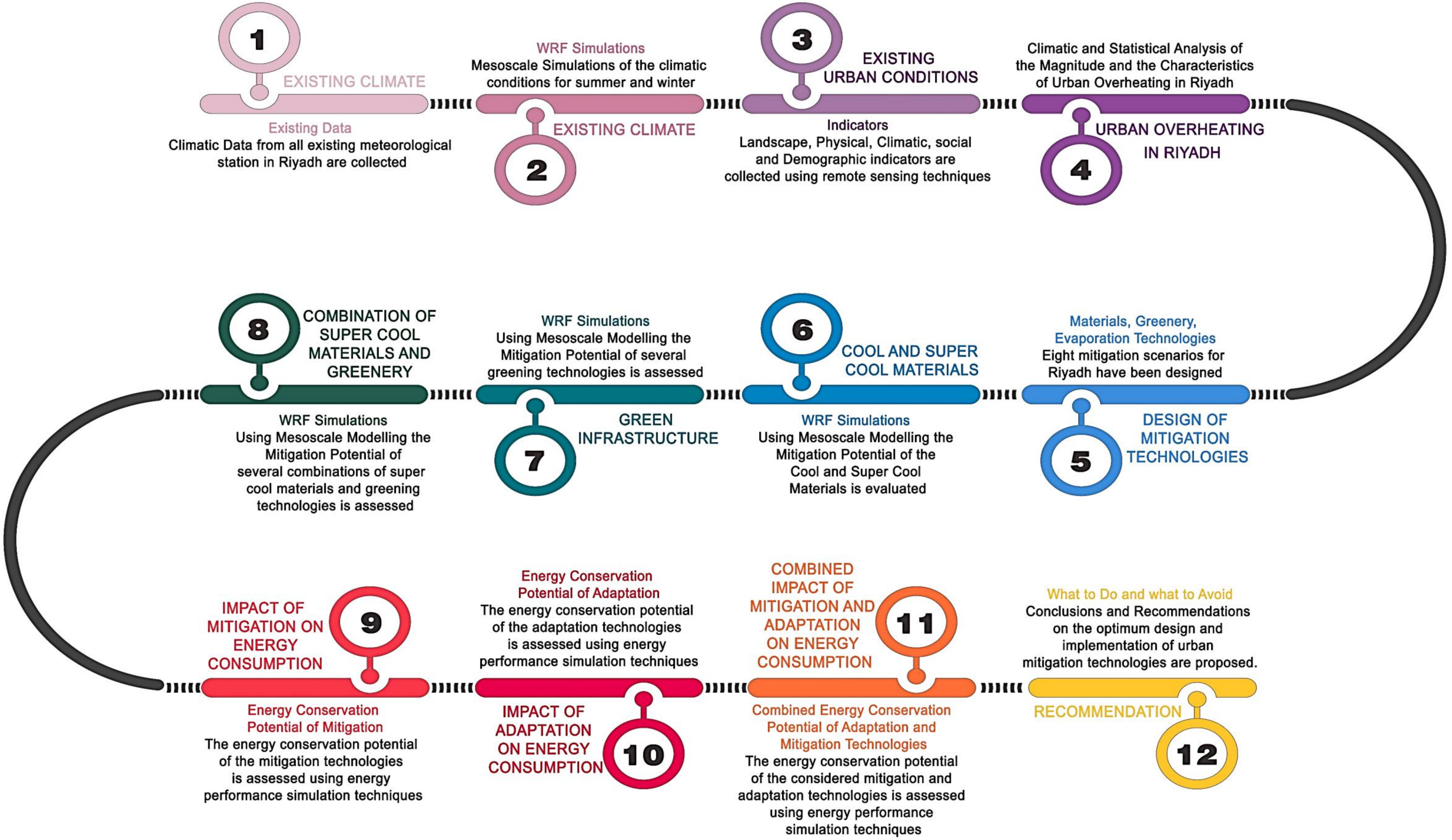
It is found that Super Cool Materials present almost 10-15 C lower surface temperature than the conventional reflecting white coatings.

In parallel, the use of Super Cool Materials can decrease the surface temperature of dark color cities up to 30 C

Reference Conditions



1. To assess the magnitude of urban overheating in the city, the magnitude of the UHI, and the intensity of heatwaves in the city, based on the measured data.
2. To assess the hot spots in the city and classify the severity of urban overheating in various parts of the city, thermal comfort, and thermal heat risk.
3. To perform a land use/land cover analysis of Riyadh.
4. To identify the main causes of urban overheating in the city.
5. To define the most appropriate urban mitigation technologies for the whole city involving the use of advanced materials, greenery, and varying combinations of them.
6. To evaluate the cooling potential and the distribution of the main climatic parameters in the whole city for each of the considered mitigation scenarios.
7. To prepare detailed maps of the main climatic parameters in the city for each of the considered mitigation scenarios under the main synoptic climatic conditions.
8. To prepare a full climatic mapping of the cooling potential in the city and prioritise strategies to cool Riyadh.
9. To assess the impacts of each mitigation strategy on the energy consumption of the buildings in Riyadh (an urban energy assessment)
10. To assess the building retrofit strategies and investigate the combined effects of mitigation and adaptation techniques.


1
EXISTING CLIMATE
Existing Data
Climatic Data from all existing meteorological station in Riyadh are collected
WRF Simulations
Mesoscale Simulations of the climatic conditions for summer and winter
2
EXISTING CLIMATE
3
EXISTING URBAN CONDITIONS
Indicators
Landscape, Physical, Climatic, social and Demographic indicators are collected using remote sensing techniques
Climatic and Statistical Analysis of the Magnitude and the Characteristics of Urban Overheating in Riyadh
URBAN OVERHEATING IN RIYADH
4
Materials, Greenery, Evaporation Technologies
Eight mitigation scenarios for Riyadh have been designed
5
DESIGN OF MITIGATION TECHNOLOGIES
6
COOL AND SUPER COOL MATERIALS
WRF Simulations
Using Mesoscale Modelling the Mitigation Potential of the Cool and Super Cool Materials is evaluated
WRF Simulations
Using Mesoscale Modelling the Mitigation Potential of several greening technologies is assessed
7
GREEN INFRASTRUCTURE
8
COMBINATION OF SUPER COOL MATERIALS AND GREENERY
WRF Simulations
Using Mesoscale Modelling the Mitigation Potential of several combinations of super cool materials and greening technologies is assessed
IMPACT OF MITIGATION ON ENERGY CONSUMPTION
9
Energy Conservation Potential of Mitigation
The energy conservation potential of the mitigation technologies is assessed using energy performance simulation techniques
Energy Conservation Potential of Adaptation
The energy conservation potential of the adaptation technologies is assessed using energy performance simulation techniques
IMPACT OF ADAPTATION ON ENERGY CONSUMPTION
10
COMBINED IMPACT OF MITIGATION AND ADAPTATION ON ENERGY CONSUMPTION
11
Combined Energy Conservation Potential of Adaptation and Mitigation Technologies
The energy conservation potential of the considered mitigation and adaptation technologies is assessed using energy performance simulation techniques
What to Do and what to Avoid
Conclusions and Recommendations on the optimum design and implementation of urban mitigation technologies are proposed.
RECOMMENDATION
12

Mitigation Scenarios – Reflective Materials

Reference Riyadh: Climatic evaluation of the whole Riyadh area for 3 summer months and one winter month under the existing conditions without application of mitigation measures.

Reflective Riyadh: Modified high albedo in the whole city of Riyadh. Roofs and pavements with higher albedo than the base case is considered for the whole urban area of Riyadh (albedo of roofs: 0.75, albedo of pavements: 0.40).

Super Reflective Riyadh: Modified very high albedo in the whole city of Riyadh. Citywide implementation of super cool material in roofs with an albedo of 0.95 and emissivity of 0.95. No modification of the albedo of pavements, as under the current conditions.

Mitigation Scenarios - Greenery

Green and Dry Riyadh: Increase of the green infrastructure of Riyadh up to 30% of its surface using non-irrigated low-level vegetation. Albedo as under the current conditions.

Very Green and Dry Riyadh: Increase of the green infrastructure of Riyadh up to 60% of its surface, using non -irrigated low-level vegetation. Albedo as under the current conditions.

Green and Irrigated Riyadh: Increase of the green infrastructure of Riyadh up to 30% of its surface, using irrigated low-level vegetation. Albedo as under the current conditions.

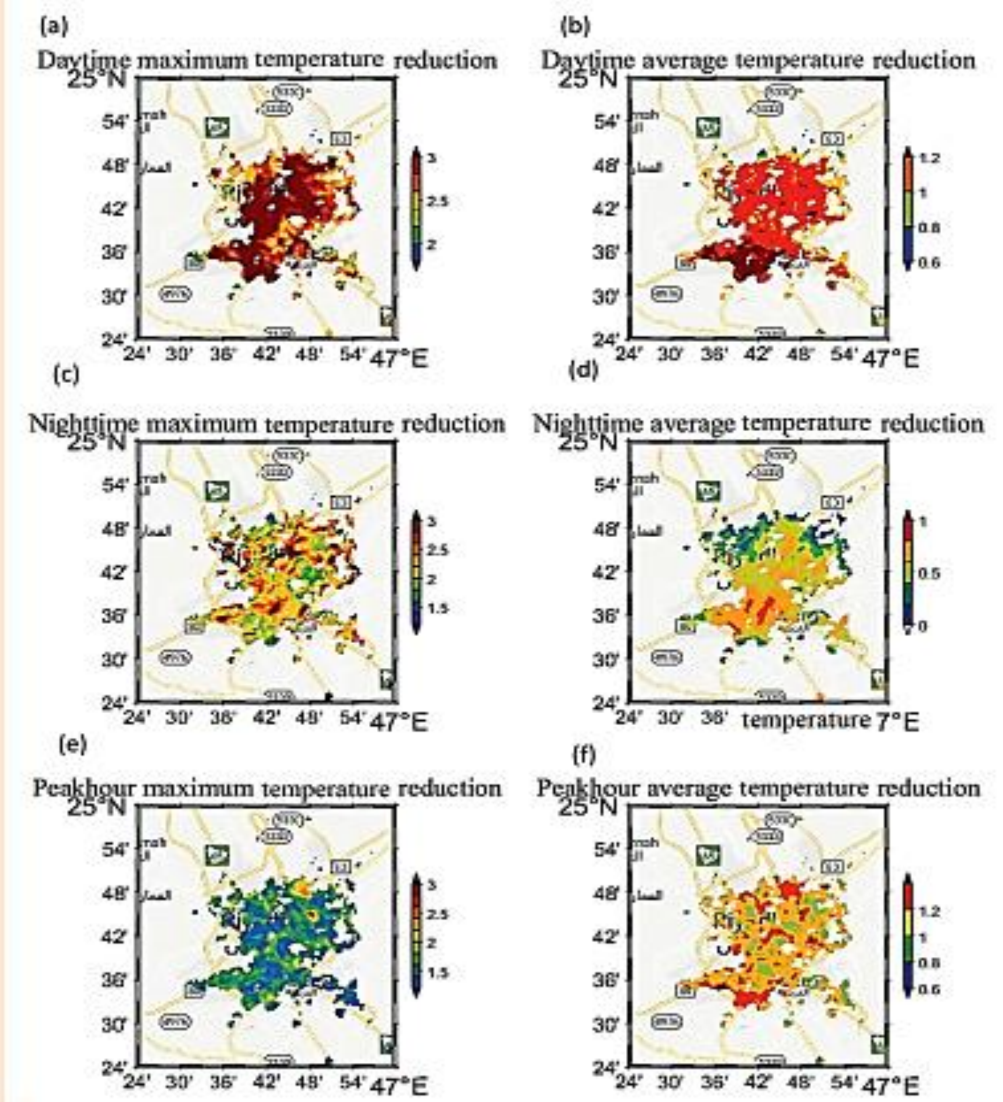
Very Green and Irrigated Riyadh: Increase of the green infrastructure of Riyadh up to 60% of its surface, using irrigated high-level vegetation. Albedo as under the current conditions.

Combined Mitigation Scenarios

Very Green – Very Reflective and Dry Riyadh: Combined case - increase of the green infrastructure of Riyadh up to 60% of its surface, using non-irrigated low-level vegetation combined with citywide implementation of super cool material in roofs with an albedo of 0.95 and emissivity of 0.95. No modification of the albedo of pavements, as under the current conditions.

Very Green – Very Reflective and Irrigated Riyadh: Combined case - increase of the green infrastructure of Riyadh up to 60% of its surface, using irrigated high-level vegetation combined with citywide implementation of super cool material in roofs with an albedo of 0.95 and emissivity of 0.95. No modification of the albedo of pavements, as under the current conditions.

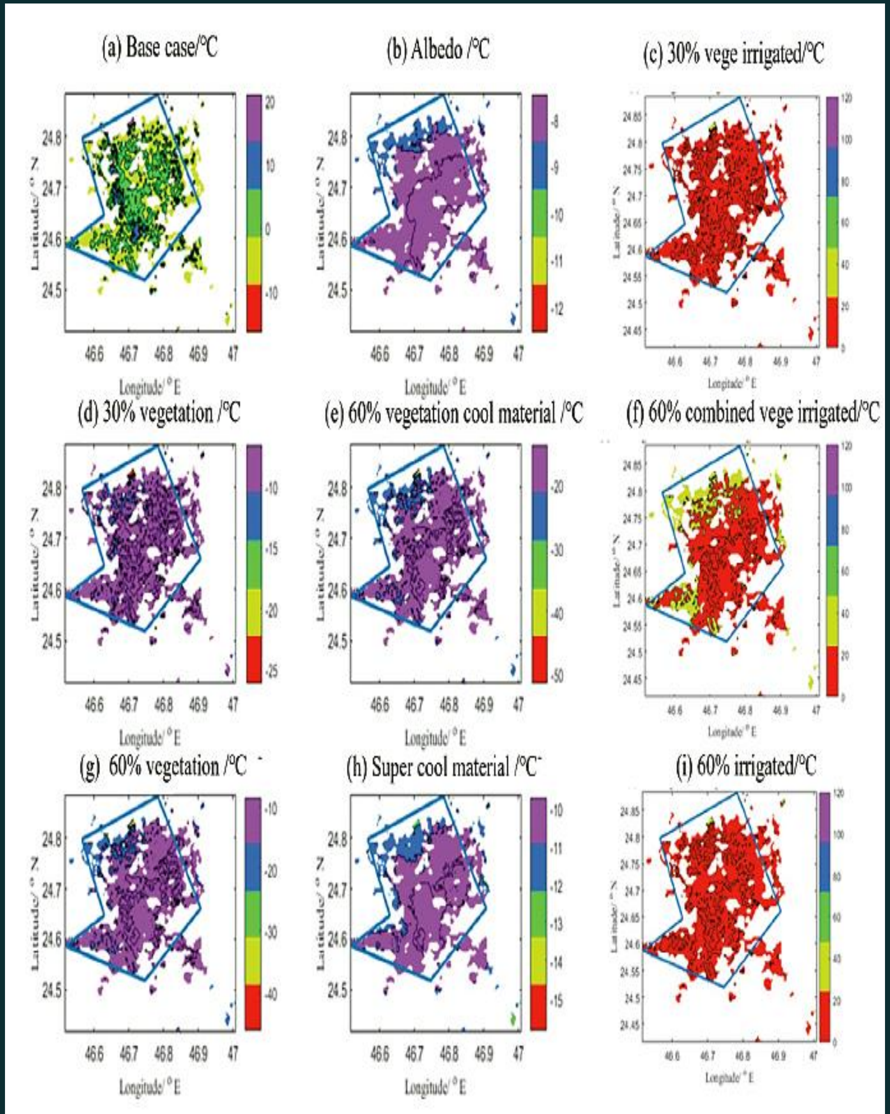
Reflective Riyadh – Ambient Temperature

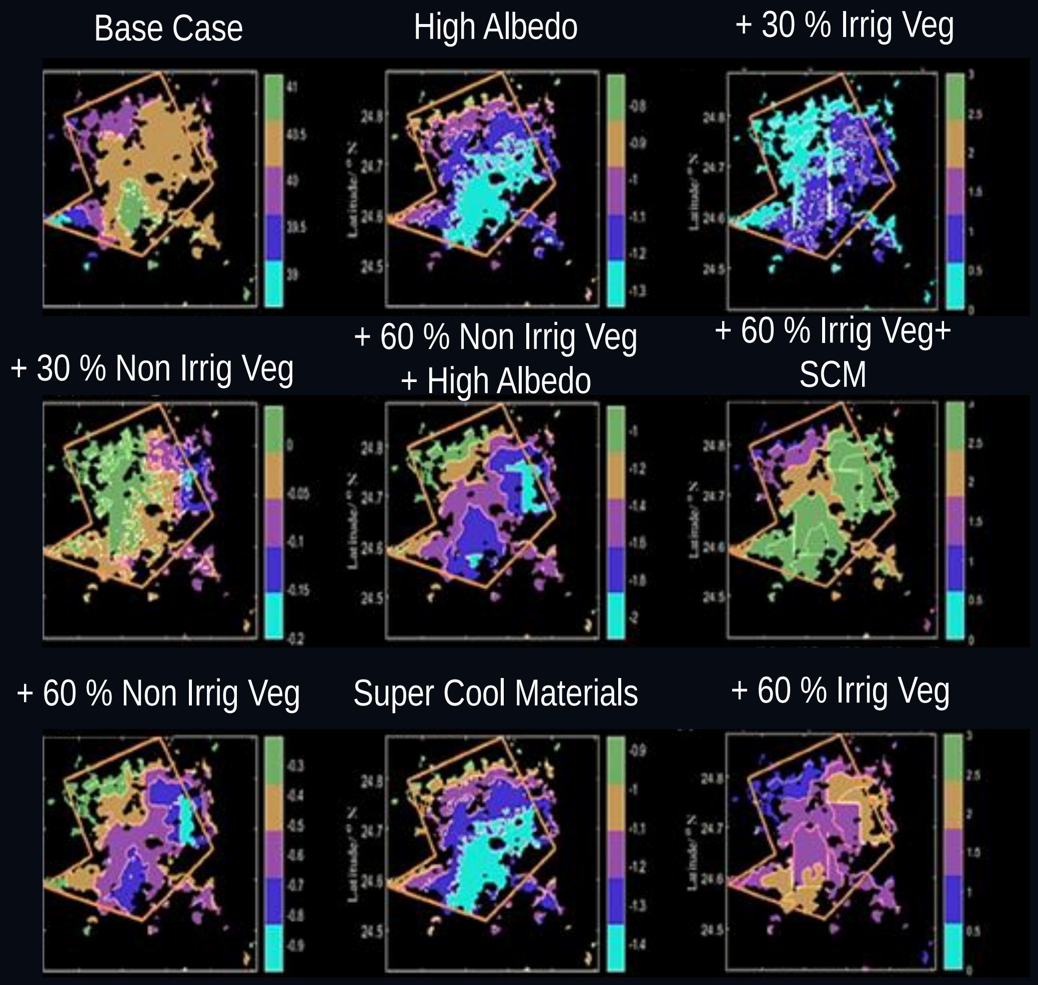


Comparative Analysis - Conclusions

1. All mitigation measures have a more pronounced cooling effect under hot weather conditions. The higher the background ambient temperature, the higher the cooling potential of the mitigation scenarios.
2. In vegetation related scenarios, the dry soil conditions prevent plants from releasing effective evapotranspiration during the day, and most of the latent heat flux during the day comes from the direct soil evapotranspiration. When using plants to alleviate overheating in Riyadh, adequate irrigation must be considered.
3. In high-reflective and dry Riyadh and the reflective and dry scenarios, daytime cooling is very significant.
4. In all the scenarios, the night UHI of the city dropped sharply, while the daytime UHI dropped slightly. The UHI intensity was significantly reduced in the whole city, but the more important temperature drop is observed in the southern parts of the city.
5. Cold dense air masses are advected from the terrain surrounding Riyadh into the main city during the night, resulting in more dramatic ambient temperature drop for all the scenarios. For the vegetation scenarios, due to the combined effect of Riyadh's surrounding terrain and the change of soil heat storage and surface heat transfer properties, the night-time cooling effect is much more significant than in the reflective and very reflective and dry Riyadh scenarios.
6. The use of mitigation measures has slightly reduced the northwest wind influx in the city during the daytime. The drop of wind speed is positively correlated to the temperature reduction. Although the analysis of the thickness of the planet boundary layer (PBL) shows that the vertical convection in the city has not weakened, the decrease of the northwest wind means that advection was slightly reduced. This change would reduce the heat and gas exchange between the city and the surrounding areas, possibly resulting in higher pollutants accumulation.
7. For all mitigation measures, the peak hour cooling effect depends on the magnitude of the released sensible heat flux during the day. In the Very Green, Very Reflective Irrigated Scenario, that presents the best mitigation potential, the transpiration of plants is stimulated to the greatest extent by irrigation, while the use of cool materials reduces the solar radiation received by the city. This scenario presents the highest cooling potential during the daytime.
8. For all vegetation scenarios, irrigation is a must to guarantee the functioning of evapotranspiration. Otherwise, the increased area of vegetation could offer a negligible mitigation effect.

Comparative Analysis – Nighttime Sensible





The developed Super Cool Materials have been considered as the primary heat mitigation strategy to decrease the ambient temperature and reduce the energy consumption of buildings in numerous cities.

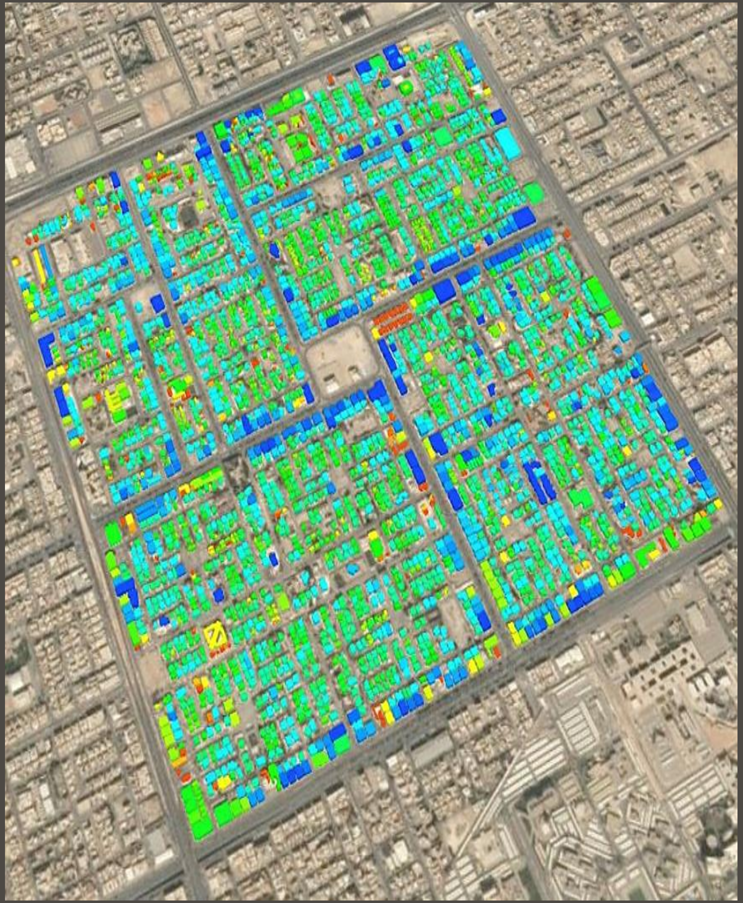
Results from the Heat Mitigation Study in Riyadh, KSA

- Use of white super cool materials in the roofs of the city, can reduce the peak daytime summer temperature up to 2.8 C

- Combined use of white SCM on the roof of buildings, with well irrigated greenery, can reduce the peak day summer ambient temperature up to 4.6 C

- Increase of the albedo in the city by 0.4 can reduce the peak daytime ambient temperature up to 1.5 C.

S. Haddad et al : **Quantifying the Energy Impact of Heat Mitigation Technologies at the Urban Scale,** Nature-Cities, 2024



The combined use of white super cool materials on the roofs of buildings with well irrigated additional greenery provides serious energy benefits during the summer period and decreases considerably the cooling demand of buildings. .

Results from the Heat Mitigation Study in Riyadh, KSA

- Use of white super cool materials in the roofs of the city, can reduce the cooling demand of buildings up to 10 %

- Combined use of white SCM on the roof of buildings, with well irrigated greenery, can reduce the cooling demand of buildings up to 17 %.

- Combined use of white SCM on the roof of buildings, with well irrigated greenery and energy adaptation measures can reduce the cooling demand of buildings up to 35 %.

S. Haddad et al : **Quantifying the Energy Impact of Heat Mitigation Technologies at the Urban Scale,** Nature-Cities, 2024

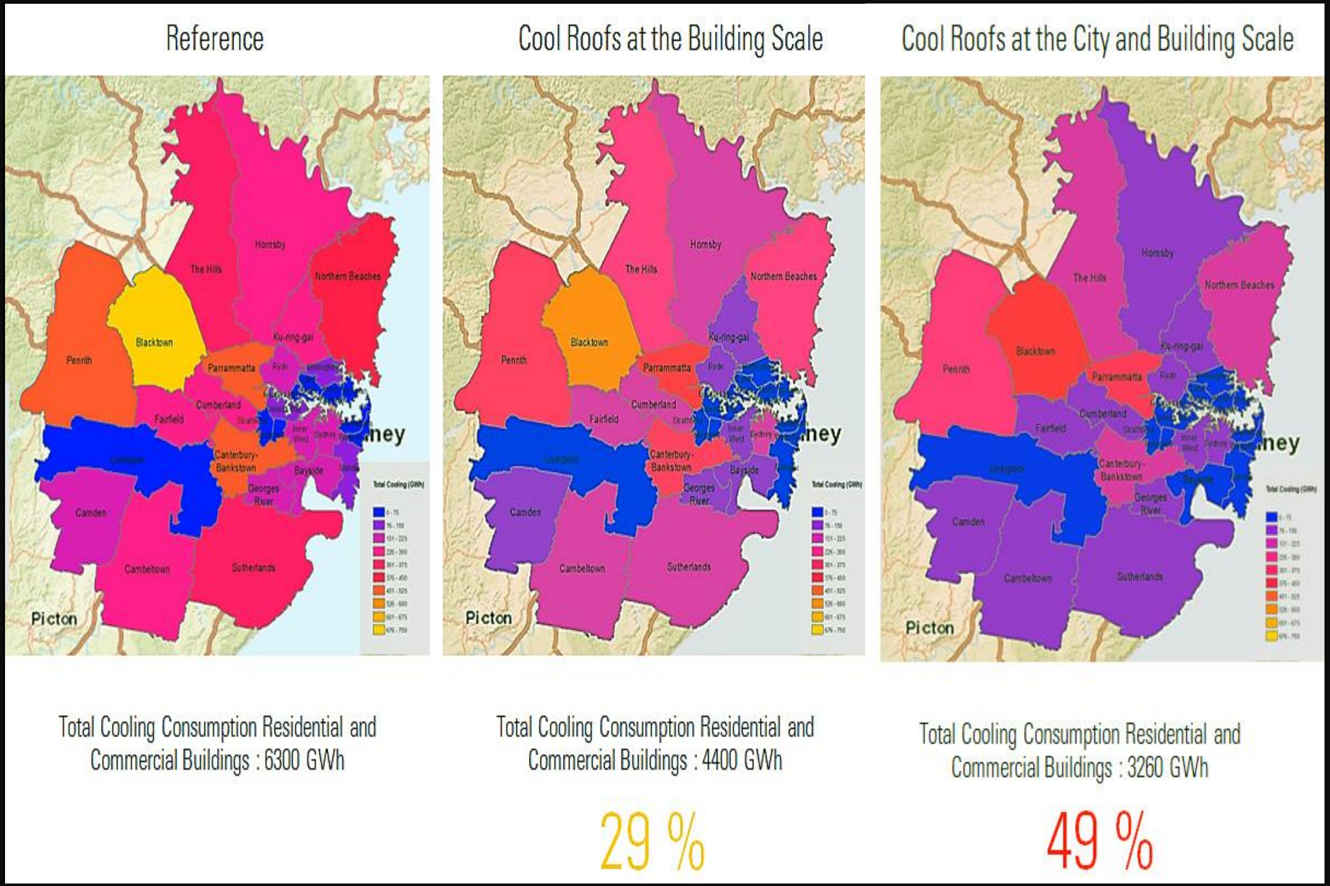
Conclusions and proposals

Riyadh suffers from an important degree of overheating. The temperature of the city is up to 4°C higher than that of the surrounding suburban ambient zones.

Major Conclusions

1. Riyadh suffers from an important degree of overheating. The temperature of the city is up to 4°C higher than that of the surrounding suburban ambient zones.
2. Overheating increases significantly the levels of discomfort as well as the heat risk, especially in the southern and eastern parts of the city.
3. Implementation of mitigation technologies in Riyadh involving use of reflective materials for roofs and pavements as well as of high-level irrigated trees can decrease the peak daily temperature up to 2.5°C.
4. Non-irrigated vegetation has a very minor impact on the local climate and may even increase the temperature of the city during the daytime. In parallel, non-irrigated vegetation may increase the level of local pollutants because of the increased Biogenic Volatile Organic Compounds (BVOC) emissions.
5. Well-irrigated vegetation can contribute considerably to improve the local climate of the city and decrease the peak daily temperature up to 1.4°C. However, this is an effective but long-term mitigation strategy as additional green infrastructure may have a limited impact during the first 10 years.
6. The use of reflective and super reflective materials is a very efficient mitigation technology that can contribute strongly to improve the local climate and decrease the peak ambient temperature up to 1.8°C. The use of reflective and super reflective materials can offer an immediate impact on the climate of the city.
7. Implementation of mitigation technologies in Riyadh has a tremendous impact on the local climate during the whole year and can decrease summer overheating period up to 35%.
8. Implementation of mitigation technologies in Riyadh has a significant impact on the cooling energy consumption of buildings. The combined implementation of reflective materials and well-irrigated greenery technologies can reduce the cooling energy consumption of buildings up to 16%.
9. The combined use of building adaptation and urban mitigation technologies in Riyadh can have a tremendous impact on the energy consumption of buildings and reduce their cooling needs up to 35%.

Energy Impact of Heat Mitigation Technologies



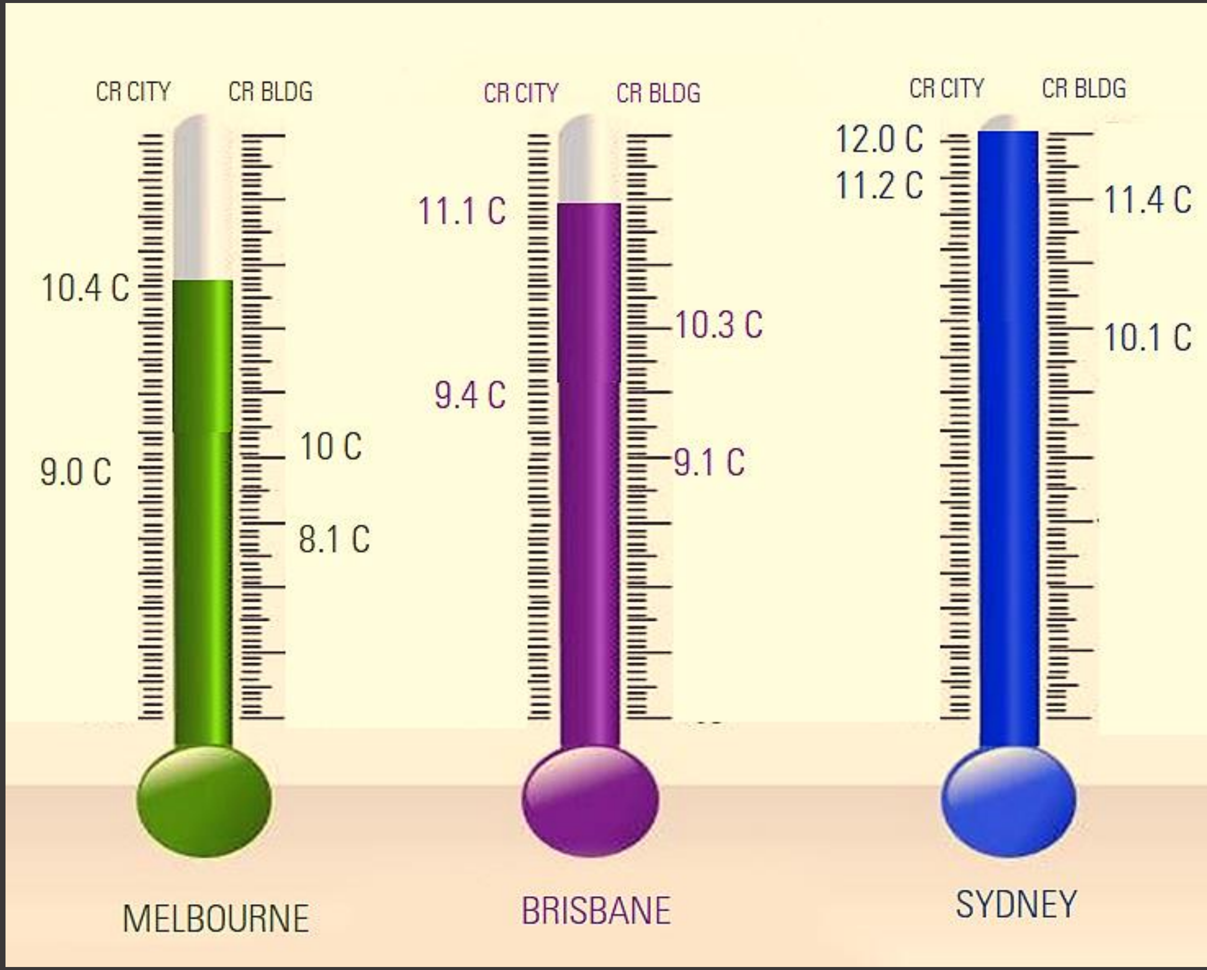
A study has been performed by the Department of Industry in Australia to assess the impact of cool roofs in the major Australian cities has concluded that:

Main Results of the Study

In average, when cool roofs are implemented in all buildings of Sydney, can contribute to reduce the sensible cooling load of the residential and commercial buildings in the city by 29 %

When, the indirect impact of cool roofs is taken into account involving the decrease of the ambient temperature and the increase of the efficiency of the A/C, then the contribution can reach 49 %

S. Garshasbi, Jie Feng, Riccardo Paolini, Jean Jonathan Duverge ,Carlos Bartesaghi-Koc, Samaneh Arasteh, Ansar Khan, M. Santamouris : On the energy impact of cool roofs in Australia, Energy and Buildings, Volume 278, 1 January 2023, 112577



A study has been performed by the Department of Industry in Australia to assess the impact of cool roofs in the major Australian cities has concluded that:

Main Results of the Study

The implementation of cool roofs in low income houses in Australia, not insulated buildings can decrease the peak indoor summer temperature up to 12 C.

Cool Roofs can improve tremendously thermal comfort during the warm period of the year and decrease substantially heat related mortality and morbidity

S. Garshasbi, Jie Feng, Riccardo Paolini, Jean Jonathan Duverge ,Carlos Bartesaghi-Koc, Samaneh Arasteh, Ansar Khan, M. Santamouris : On the energy impact of cool roofs in Australia, Energy and Buildings, Volume 278, 1 January 2023, 112577

"Somehow we need to monetise this - and quickly"

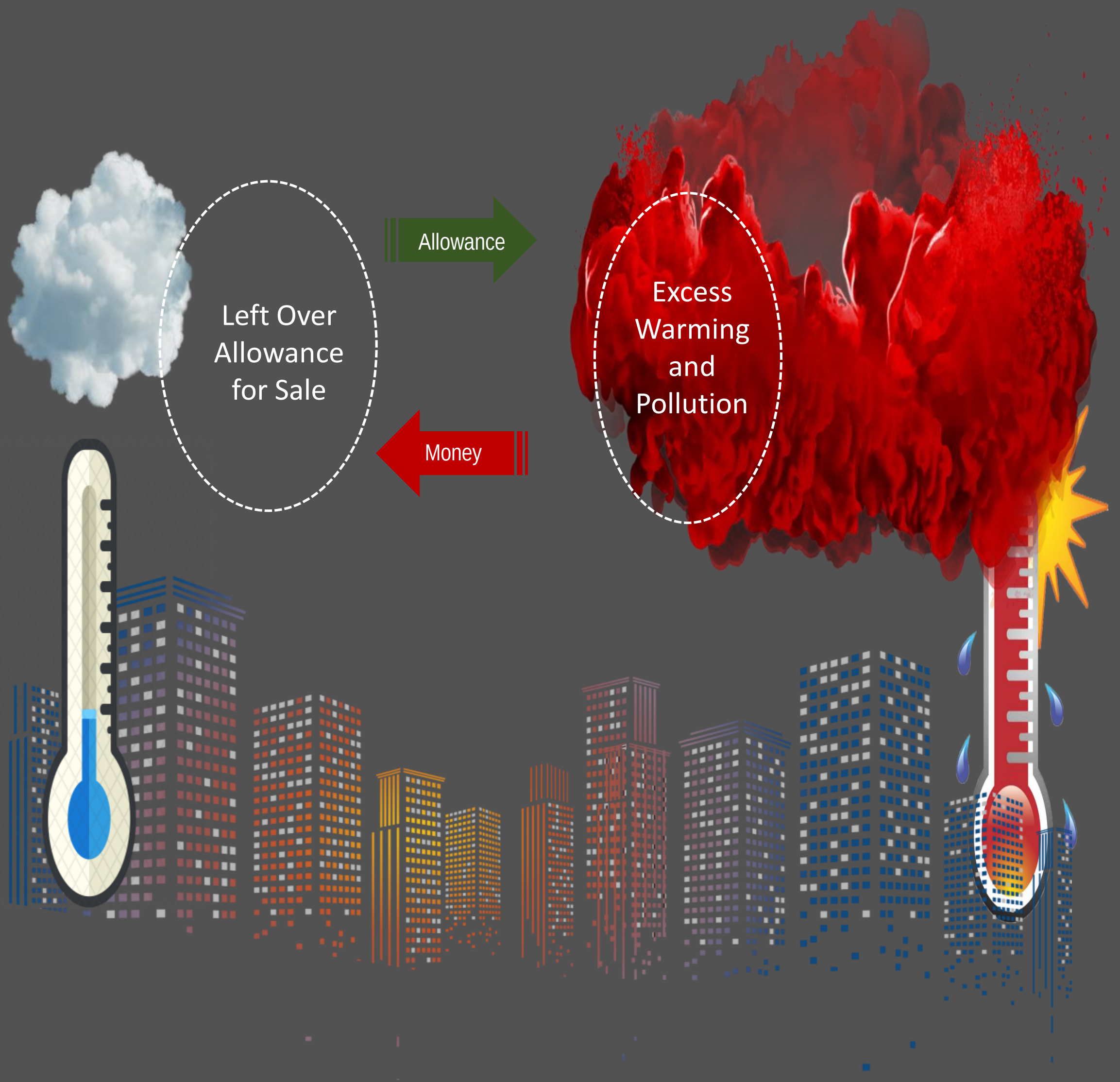
Establishment of Urban Warming Markets

Setting as a goal a minimum urban overheating and pollution involves limiting the strength of warming and polluting sources and increasing the strength of urban heat sinks to balance the urban heat budget.

Achieving a Zero Urban Thermal and Pollution budget requires to:

Change the way we design, build and operate urban buildings, spaces and infrastructures and transition to less warming and polluting patterns and policies

Put a value on the urban mitigation and adaptation capital that limits the strength of local climate change and environmental quality



Putting a Price on Urban Warming

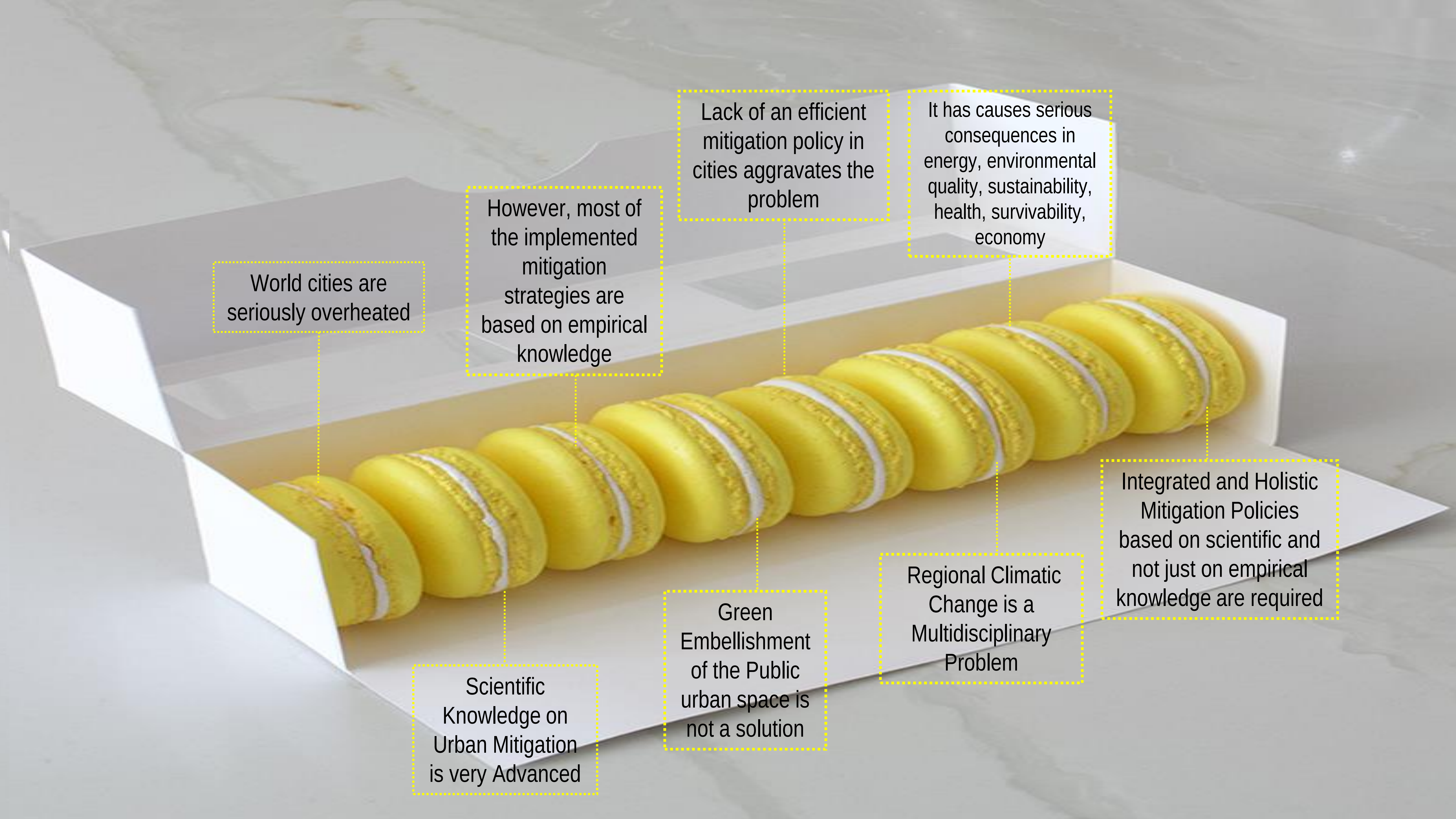
The magnitude of overheating and pollution caused by selected major urban activities has to be assessed and controlled.

Liable entities exceeding the threshold and causing urban warming must pay a price for every warming or pollution unit, shortfall cost, or to surrender the appropriate number of allocated units.

Boosting Sustainable Urban Investments

To accelerate urban cooling and finance urban heat mitigation and adaptation it is critical to value urban overheating with liquidity.

The development of a voluntary Urban Warming Market could bring urban mitigation and adaptation investments sooner to the market and make them more affordable.


World cities are seriously overheated
However, most of the implemented mitigation strategies are based on empirical knowledge
Lack of an efficient mitigation policy in cities aggravates the problem
It has causes serious consequences in energy, environmental quality, sustainability, health, survivability, economy
Integrated and Holistic Mitigation Policies based on scientific and not just on empirical knowledge are required
Regional Climatic Change is a Multidisciplinary Problem
Green Embellishment of the Public urban space is not a solution
Scientific Knowledge on Urban Mitigation is very Advanced

Investing and Counterbalancing the Urban Climate Change is the Next Productivity Engine to Drive Growth

The serious heterogeneity of the quantitative and qualitative conclusions drawn by the existing studies can be mainly attributed to the differentiation of the synergetic association of energy, pollution, health and vulnerability in the considered cases

The need to adopt a more extended and interdisciplinary frame for impact studies considering all possible synergies is quite evident.
Studies on the impact of overheating on energy, pollution, vulnerability and health, provide knowledge on the specific impact on energy consumption, peak electricity, efficiency of the power plants, concentration of ozone, emission of power plants, vulnerability and health.

While the provided information is rich in quantified data, it is highly fragmented and fails to consider the problem of the overheating impact in an integrated and holistic way.