A discussion on the paper

"Magnitude of urban heat islands largely explained by climate and population "

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Video Conference

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Discussion on a paper

ARTICLE

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Magnitude of urban heat islands largely explained by climate and population

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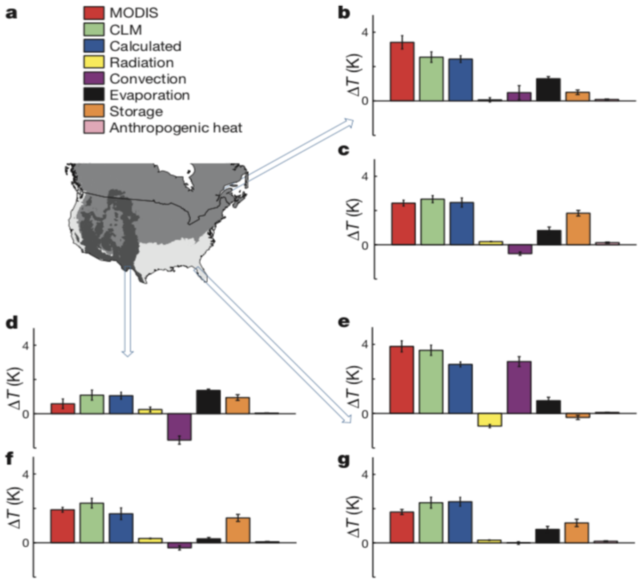
Urban heat islands (UHIs) exacerbate the risk of heat-related mortality associated with global climate change. The intensity of UHIs varies with population size and mean annual precipitation, but a unifying explanation for this variation is lacking, and there are no geographically targeted guidelines for heat mitigation. Here we analyse summertime differences between urban and rural surface temperatures (ΔT_s) worldwide and find a nonlinear increase in ΔT_s with precipitation that is controlled by water or energy limitations on evapotranspiration and that modulates the scaling of ΔT_s with city size. We introduce a coarse-grained model that links population, background climate, and UHI intensity, and show that urban–rural differences in evapotranspiration and convection efficiency are the main determinants of warming. The direct implication of these nonlinearities is that mitigation strategies aimed at increasing green cover and albedo are more efficient in dry regions, whereas the challenge of cooling tropical cities will require innovative solutions.

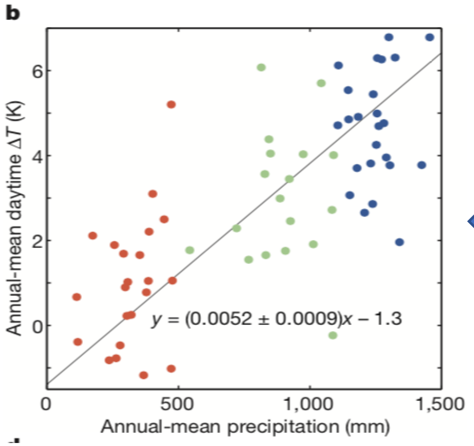
Outline

- 1. Background
- 2. Research Method
- 3. Results and Discussion
- 4. Conclusion

1. Background

- The Urban Heat Islands (UHIs) have a profound impact on human health and regional climate.





- ΔT ~ precipitation (P) : linear relationship
- Convection efficiency was the dominant driver.

(Zhao et al., 2014)

Different points

1. **Quadratically Nonlinear**

---- 32 cities, China (Zhou et al., 2016)

2. Numerical simulation results --- **nonlinear response**, change in **rural temperature** rather than convection efficiency. (Gu and Li, 2018)

Knowledge Gap:

ΔT ~ P: **causal links remain unclear**

1. Background

A case in point:

1. Matera (Italian city) exhibits **a negative UHI**. (Richards et al., 2017)

----- dense urban fabric and **lowest green cover** in Europe (<1%)

2. Singapore shows a daytime ΔT_s **of +1.9 ^{o}C** (Richards et al., 2017)

------ **more than 50% green spaces**.

Hence, the efficiency of heat mitigation strategies cannot be inferred directly from studies on a few selected cities.

------ there is no adequate basis for generalization.

1. Background --- objectives

Objective 1: Determining the effect of precipitation and population together on the UHI intensity on a global scale.

Objective 2: Evaluating the efficiency of different (increasing urban green cover and urban albedo etc.) UHI mitigation strategies in different regions of the world.

2. Research Method

Method:

Data acquisition:

on global scale

Model: input variables:

Only depend on annual mean precipitation and population

2. Research Method: Data Sources

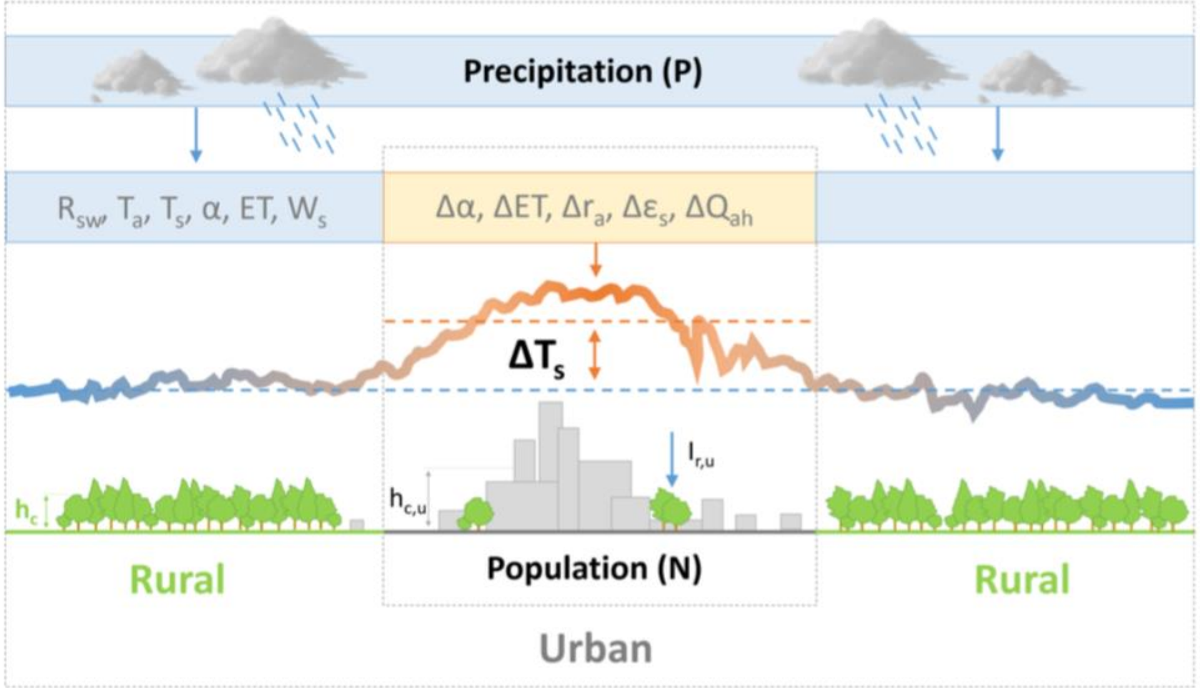
Variable	Spatial resolution	Temporal resolution	Period	Source
UHI intensity (ΔT_s)	Urban extent [*]	Summertime	2013	CIESIN
Background temperature (T_s)	Rural buffer [†]	Summertime	2013	CIESIN
Population (N)	Urban entent [*]	Year	2000	CIESIN
Mean annual precipitation (P)	$0.5° \times 0.667°$	Monthly	2010-2013	GPCC
	$0.5° \times 0.667°$	Monthly	2013	MERRA
Background climate (T_s, T_a, R_{sw}, $R_{sw,net}$, W_s, q_a, p_{atm})	$0.5° \times 0.667°$	Monthly	2013	MERRA
Urban/rural albedo (α, α_u)	1 km	16-day	2013	MODIS
Urban green cover ($g_{c,u}$)	Urban area (EU)	-	2012	Eurostat (2016)
	Urban area (SEA)	-	2012	Richards et al. (2017)

[*] Urban extent is estimated from nighttime lights, settlement points, and population counts (CIESIN, 2016).

[†] The rural area consists of a 10 km buffer region surrounding the urban extent (CIESIN, 2016).

- **Summer mean daily**: $\Delta T_s = (\Delta T_{s,d} + \Delta T_{s,n})/2$
- **Period:** 2013 summer average value
- **Spatial**: based on the urban and rural coordinate provided by GUHI

2. Research Method: Model principle



- Surface energy balance analysis (Lee et al., 2011; Zhao et al., 2014)
- The total ΔT is partitioned into contributions from the differences between the urban and rural land units.

$$\Delta T_s = \frac{1}{f_s - \frac{\gamma}{a_T} f_a} \Delta S; \quad (1)$$

$$\Delta S = -R_{sw}\Delta\alpha + \sigma\left(\varepsilon_a T_a^4 - T_s^4\right)\Delta\varepsilon_s - \lambda\rho\frac{q_{sat,s} - q_a}{r_a + r_c}\left(\beta\Delta g_c + g_c\Delta\beta\right) + \\ + \left(\rho c_p \frac{T_s - T_a}{r_a^2} + \lambda g_c \beta \rho \frac{q_{sat,s} - q_a}{(r_a + r_c)^2}\right)\Delta r_a + \Delta Q_{ah}; \quad (2)$$

Input variables only depending on mean annual precipitation (*P*) and city population (*N*)

2. Research Method: Coarse-grained *UHI model* ---- Albedo

Albedo:

$$\Delta\alpha(N,P) = \alpha_u(N,P) - \alpha(P)$$

- α is the background albedo estimated from precipitation data P;

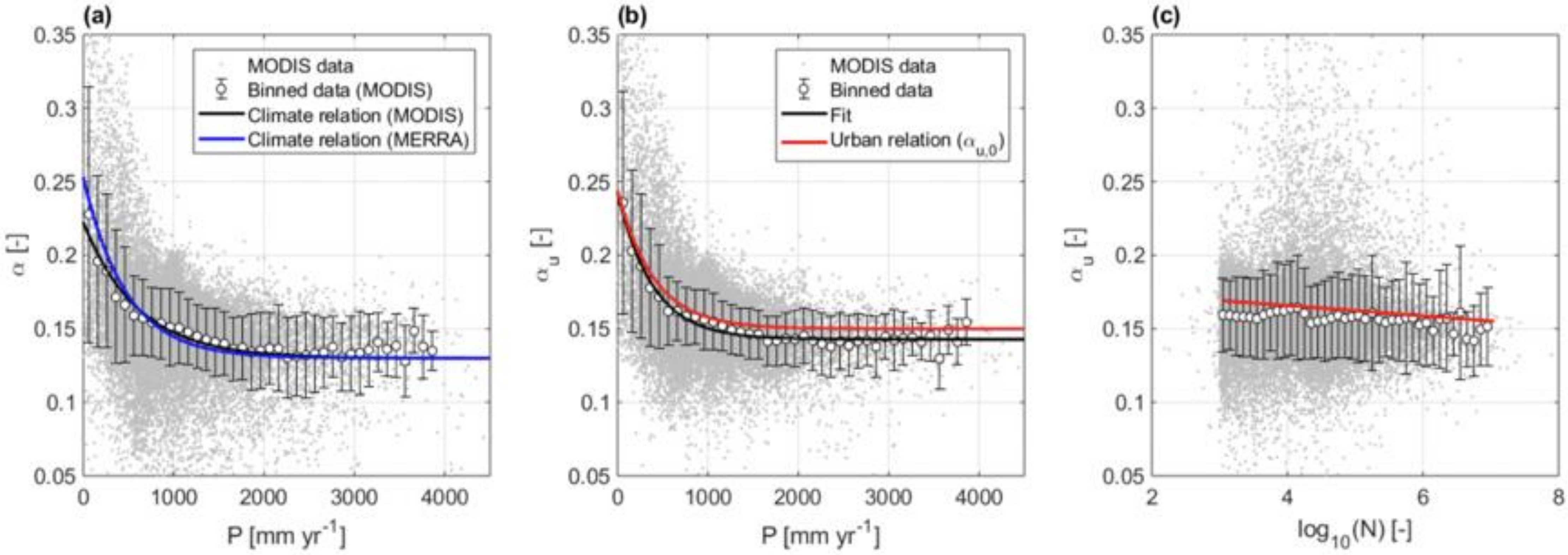
- α_u is the urban albedo.

$$\alpha_u(N,P) = (1 - gc_{,u}(P)) \cdot \alpha_{u,0}(N,P) + g_{c,u}(P) \cdot \alpha(P)$$

- $g_{c,u}$ is urban green cover (defined as the fraction of green cover to total urban area)

- $\alpha_{u,0}$ is the average albedo of the urban fabric, which depends on both climate and city size.

2. Research Method: Coarse-grained *UHI model* ---- Albedo



$$\alpha(P) = \alpha_{\alpha} \cdot \exp(b_{\alpha} \cdot P) + c_{\alpha}$$

$$\alpha_{u,o}(P, N) = \alpha_{\alpha,o} \cdot \exp(b_{\alpha o} \cdot P) - c_{\alpha 0} \cdot (log10N - d_{\alpha,o}) + e_{\alpha,o}$$

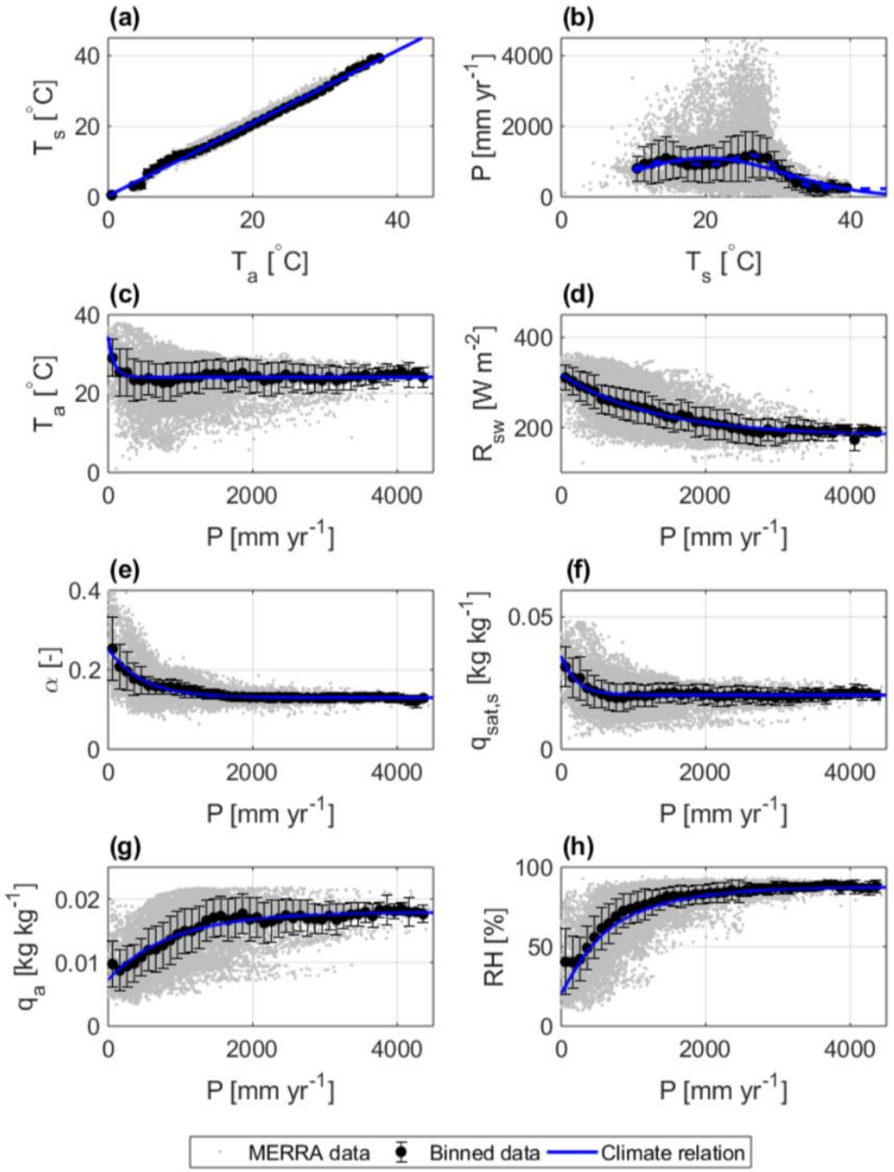
2. Method: Coarse-grained *UHI model – urban relations*

Relation	Source
Urban relations:	
$\alpha_{u,0}(P,N) = a_{\alpha 0} \cdot exp\left(b_{\alpha 0} \cdot P\right) - c_{\alpha 0} \cdot \left(log_{10} N - d_{\alpha 0}\right) + e_{\alpha 0}$	Based on MODIS data
$\rho_N(N) = \frac{N}{A_u(N)}$	-
$\rho_b(N) = 0.4 \cdot log_{10}(\rho_N) - 0.75$	Assumed
$A_u(N) = a_A \cdot N^{b_A}$	CIESIN data
$g_{c,u}(P) = \frac{a_{gc}}{1+exp\left[-b_{gc} \cdot \left(P - c_{gc}\right)\right]}$	Data from Eurostat (2016); Richards et al. (2017)
$h_{c,u}(N) = max[h_{sf}, 1.15 \cdot N^{0.12}]$	Schläpfer et al. (2015)
$Q_{ah,u}(N) = a_Q \cdot \rho_N^{b_Q}$	Data from Oke et al. (2017)
$v_{sky}(N) = cos^2\left[tan^{-1}\left(\frac{h_{c,u}(N)}{d_{c,u}}\right)\right]$	Oke (1981); Chen et al. (2012)

$$\Delta T_s = \frac{1}{f_s - \frac{\gamma}{a_T} f_a} \Delta S; \qquad (1)$$

$$\Delta S = -R_{sw}\Delta\alpha + \sigma\left(\varepsilon_a T_a^4 - T_s^4\right)\Delta\varepsilon_s - \lambda\rho\frac{q_{sat,s} - q_a}{r_a + r_c}\left(\beta\Delta g_c + g_c\Delta\beta\right) + \\ + \left(\rho c_p \frac{T_s - T_a}{r_a^2} + \lambda g_c \beta\rho\frac{q_{sat,s} - q_a}{(r_a + r_c)^2}\right)\Delta r_a + \Delta Q_{ah}; \qquad (2)$$

2. Method: Coarse-grained *UHI model – climate relations*



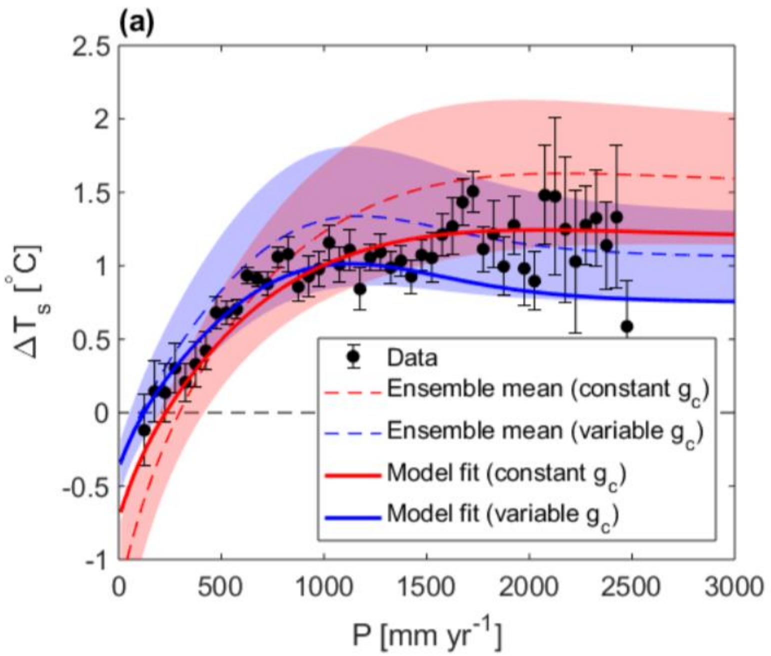
Relation	Source
Climate relations:	
$\alpha(P) = a_\alpha \cdot exp\,(b_\alpha \cdot P) + c_\alpha$	MODIS data
$h_v(P) = \frac{a_h}{1+exp[-b_h\cdot(P-c_h)]}$	ed on Madani et al. (2018)
$P(T_s) = a_P \cdot exp\left[-\left(\frac{T_s - b_P}{c_P}\right)^2\right]$	MERRA data
$q_a(P) = a_q \cdot exp\,(b_q \cdot P) + c_q$	MERRA data
$q_{sat,s}(P) = a_{qs} \cdot exp\,(b_{qs} \cdot P) + c_{qs}$	MERRA data
$R_{sw}(P) = a_R \cdot exp\,(b_R \cdot P) + c_R$	MERRA data
$T_s(T_a) = a_T \cdot T_a + b_T$	MERRA data
$T_a(P) = a_{Ta} \cdot exp\,(b_{Ta} \cdot P) + c_{Ta}$	MERRA data

- Scheme 1 :

  $\Gamma_{c,1}$(P)={T_a(P), $T_s(T_a)$. Γ(P)} **depending only on *P*.**

2. Method: Coarse-grained *UHI model* ---- *model calibration*

Symbol	Description	Units	Parameter value	Calibration interval
Urban variables and parameters:				
$\alpha_{u,0}$	Urban albedo	-	-	
Δ	Urban-Rural difference operator	-	-	
$\varepsilon_{s,u}$	Urban surface emissivity	-	-	
$\varepsilon_{u,0}$	Reference emissivity of urban fabric	-	0.9	
γ	Phenomenological parameter	-	0.1	$[0; 0.2]$
ρ_b	Building density	-	-	
ρ_N	Population density	cap km^{-2}	-	
A_u	Urban area	km^2	-	
C_D	Drag coefficient	-	1.2	
f_a	Land-surface air temperature sensitivity	W m^{-2} K^{-1}	-	
f_s	Land-surface temperature sensitivity	W m^{-2} K^{-1}	-	
$g_{c,u}$	Urban green cover	-	0.15	$[0.1; 0.3]$
$h_{c,u}$	Mean building height	m	-	
h_{sf}	Standard floor height	m	3	
$I_{r,u}$	Urban irrigation parameter	-	0.2	$[0.2; 0.5]$
m_α	Roughness parameter	-	4	
m_β	Roughness parameter	-	15	
N	Urban population	capita	$8.6 \cdot 10^5$	$[1 \cdot 10^5; 2 \cdot 10^6]$
$q'_{sat,s}$	Derivative of $q_{sat,s}$ with respect to T_s	kg kg^{-1} K^{-1}	-	



- Step 1: First the author generated a **quasi-random set** of 11 calibration parameters using **the Sobol quasi-random sampling method**.
- Step 2: Ran **Monte Carlo simulations** with the generated parameter set (1000 samples) and compared the model results with the observed P-ΔT_s relation.

2. Method: Coarse-grained *UHI model – model setup*

- **1. Explaining observed trends of ΔT_s as a function of *P, and N***

    a. the ΔT_s - P relation is modeled for different values of P with a prescribed population $N = 8.6\times10^5$ and the set of climate relations $\Gamma_{c,1}(P)$.

    b. the ΔT_s - N relation is modeled varying N for prescribed values of P and the respective variables $\Gamma_{c,1}(P)$.

2. Method: Coarse-grained *UHI model – model setup*

- 2. Assessing the impact of different urban cooling strategies on ΔT_s

  A sensitivity analysis

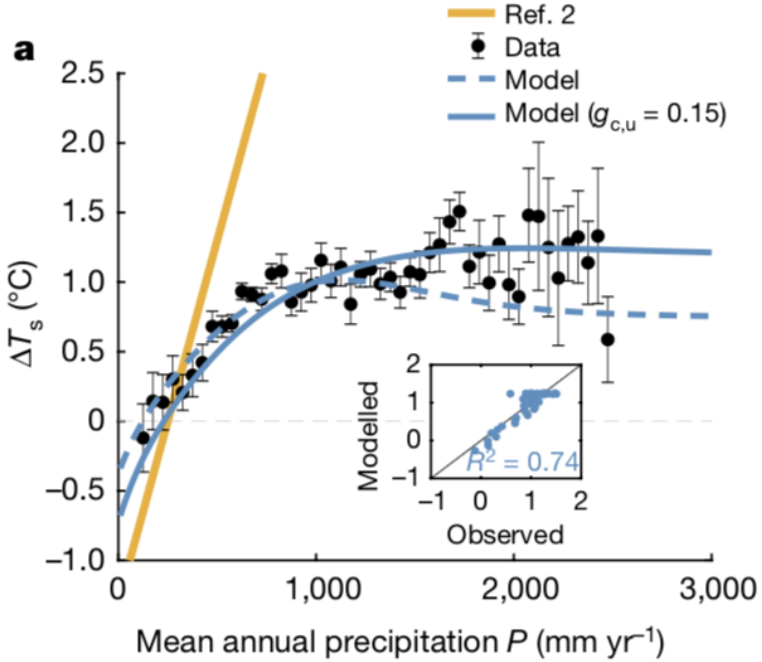
- **increasing green space** ($g_{c,u}$), **increasing albedo** ($\alpha_{u,0}$), or **decreasing density** ($\boldsymbol{\rho}_N$)
- Using P and the climate relations $\Gamma_{c,1}(P)$ as input variables.
- In the case of ($\boldsymbol{\rho}_N$), urban population is varied while maintaining a constant urban area of 100 km^2.

3. Results and discussion

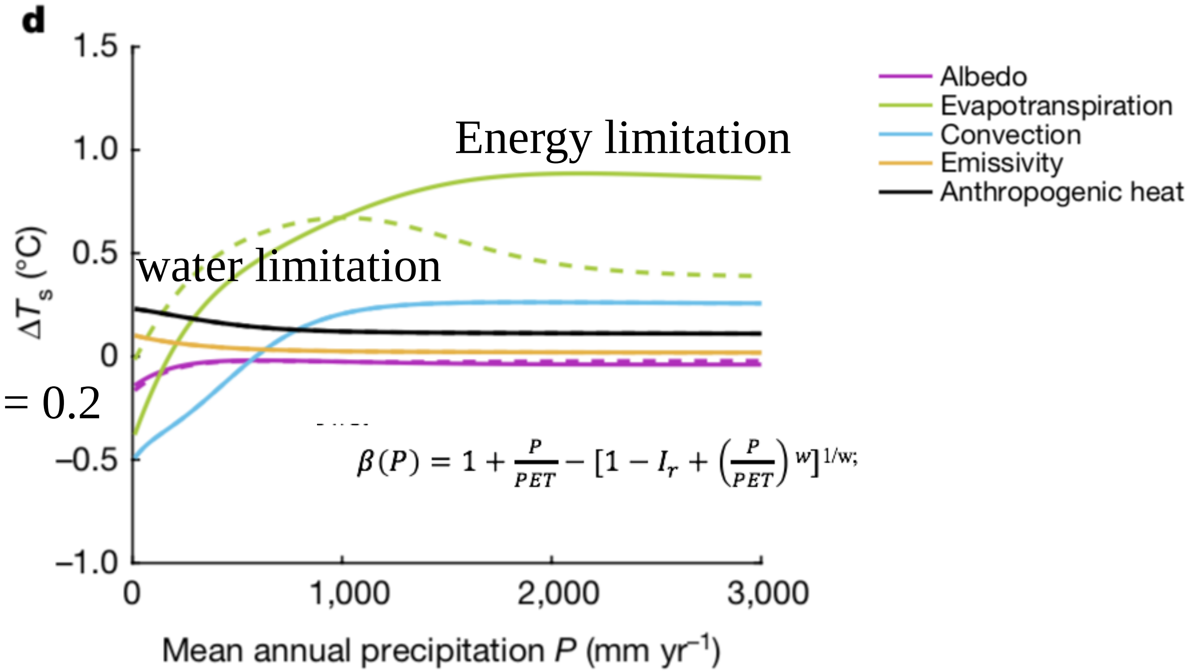
- 3.1 Global patterns of urban warming
- 3.2 Heat mitigation strategies
- 3.3 Climate-sensitive urban warming

3. 1 Global patterns of urban warming --- **precipitation**

a. the ΔT_s - P relation is modeled for different values of P with a prescribed population N =8.6×10^5 and the set of climate relations $\Gamma_{c,1}(P)$.



Irrigation: $I_{r,u}$ = 0.2



- These is a nonlinear relation between ΔT_s and mean annual precipitation ----- ΔT_s saturates when P > 1500 mm yr^{-1}.

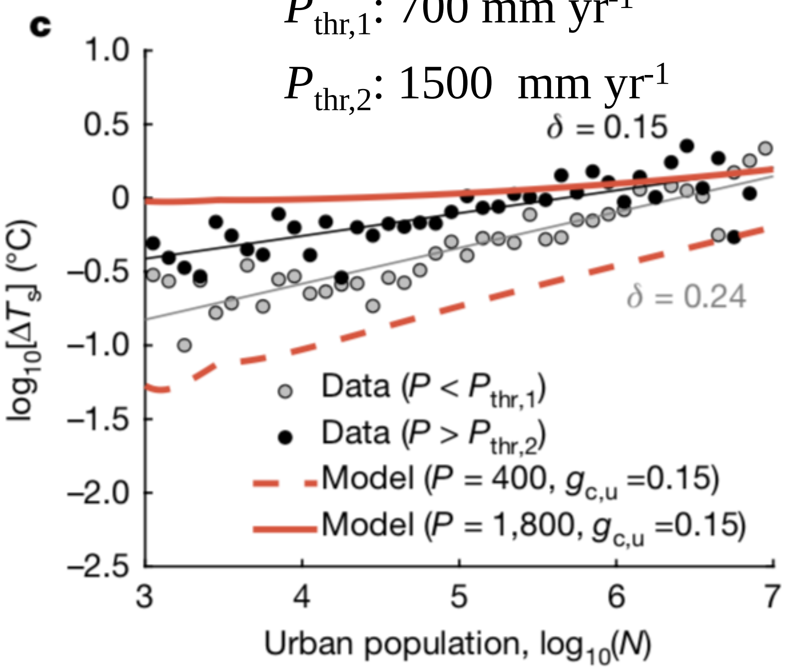
- The shape of the P-ΔT_s relation is largely controlled by changes in ET.
- Convection efficiency also contributes to city cooling in dry and warm climates.
- $\Delta\alpha$ contributes to cooling in wet regions--- negligible

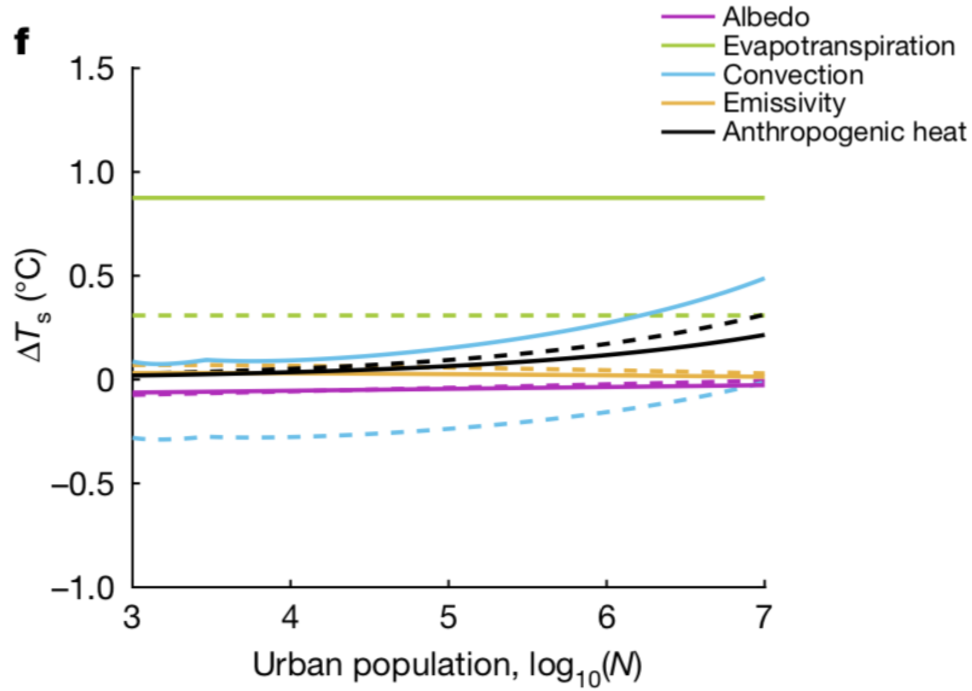
3. 1 Global patterns of urban warming --- **Population**

b. the ΔT_s - N relation is modeled varying N for prescribed values of P and the respective variables $\Gamma_{c,1}(P)$.

$P_{thr,1}$: 700 mm yr^{-1}

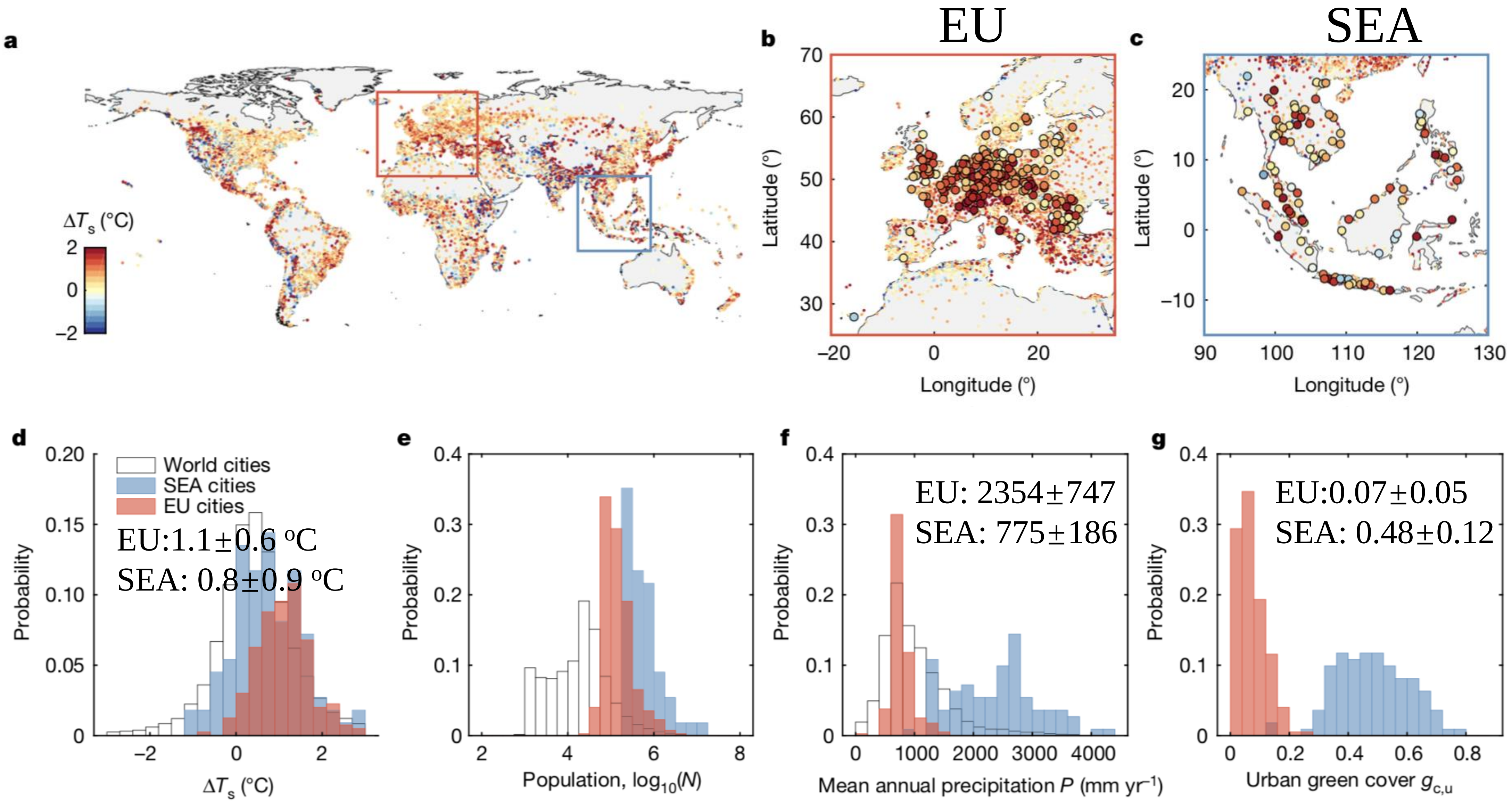
$P_{thr,2}$: 1500 mm yr^{-1}





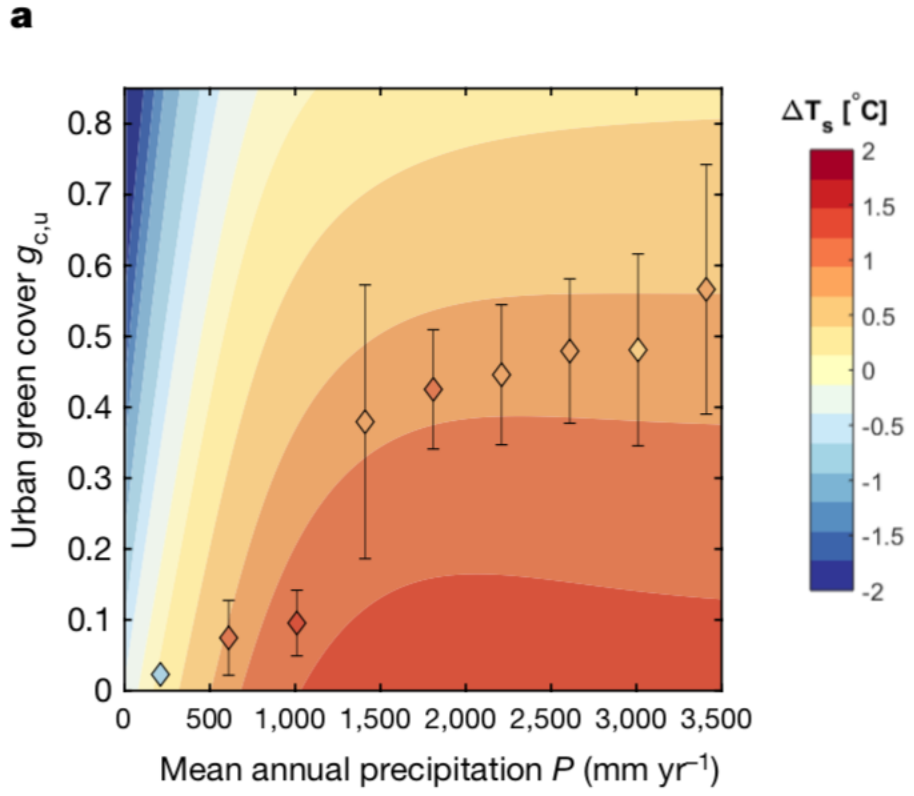
- Unlike previous results, which suggested that the scaling $\Delta \boldsymbol{T}_s \sim \boldsymbol{N}^{\sigma}$ is invariant with climate.
- σ is 0.21 globally but it varies between 0.15 and 0.34 under wet and dry conditions, respectively.
- Convection efficiency and Anthropogenic heat fluxes.

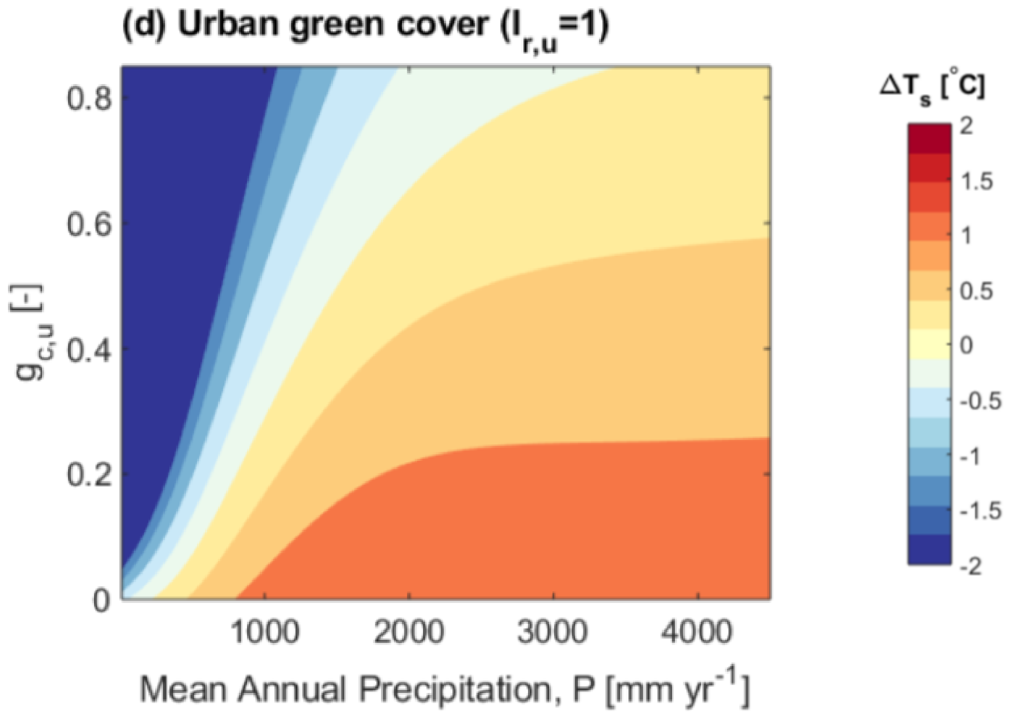
3.2 Heat Mitigation Strategies



3. 2 Heat Mitigation Strategies --- Increasing green space

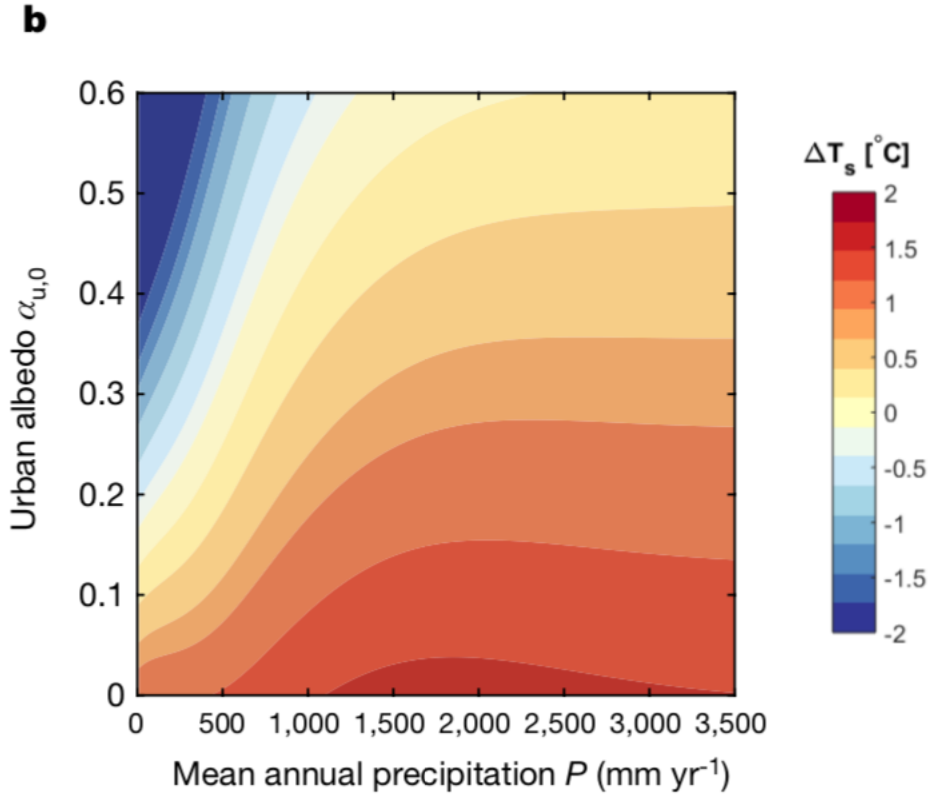
- **Increasing green space** ($g_{c,u}$), **increasing albedo** ($\alpha_{u,0}$), or **decreasing density** ($\boldsymbol{\rho}_N$)



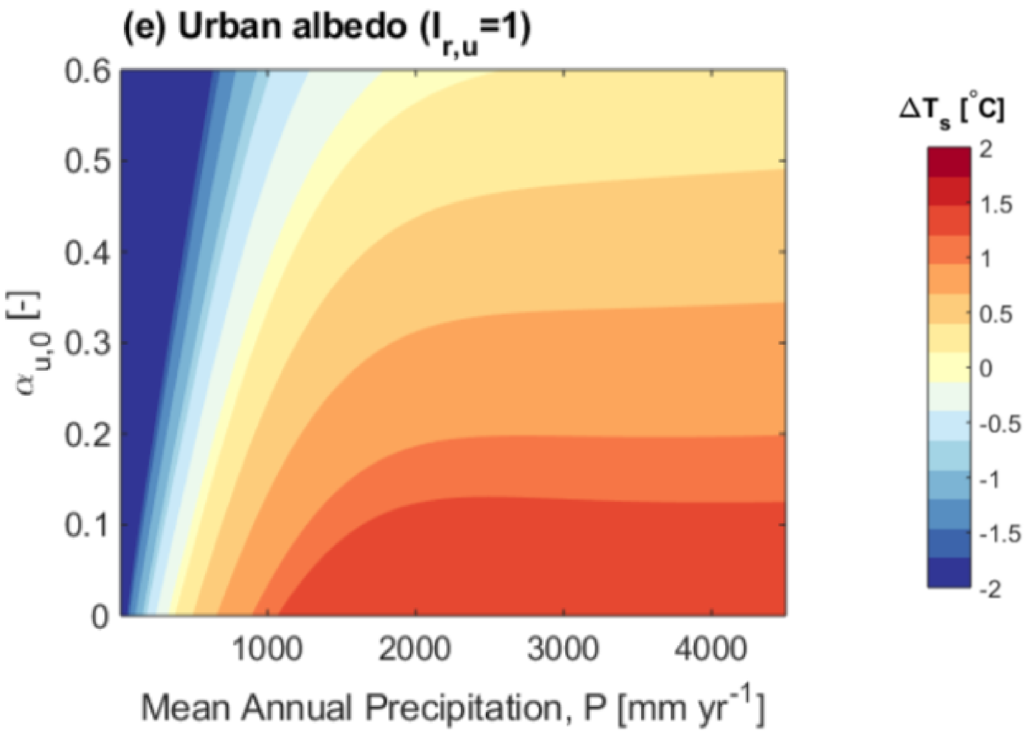


$I_u = 0$ $I_u = 1$

3. 2 Heat Mitigation Strategies --- Increasing albedo

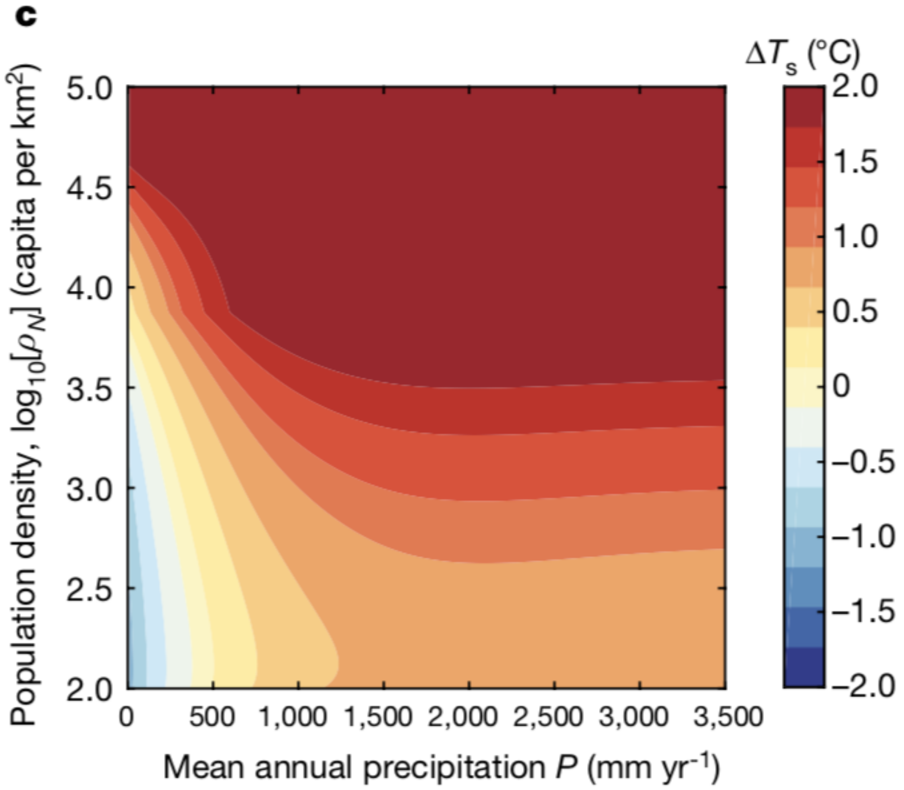


$I_u = 0$

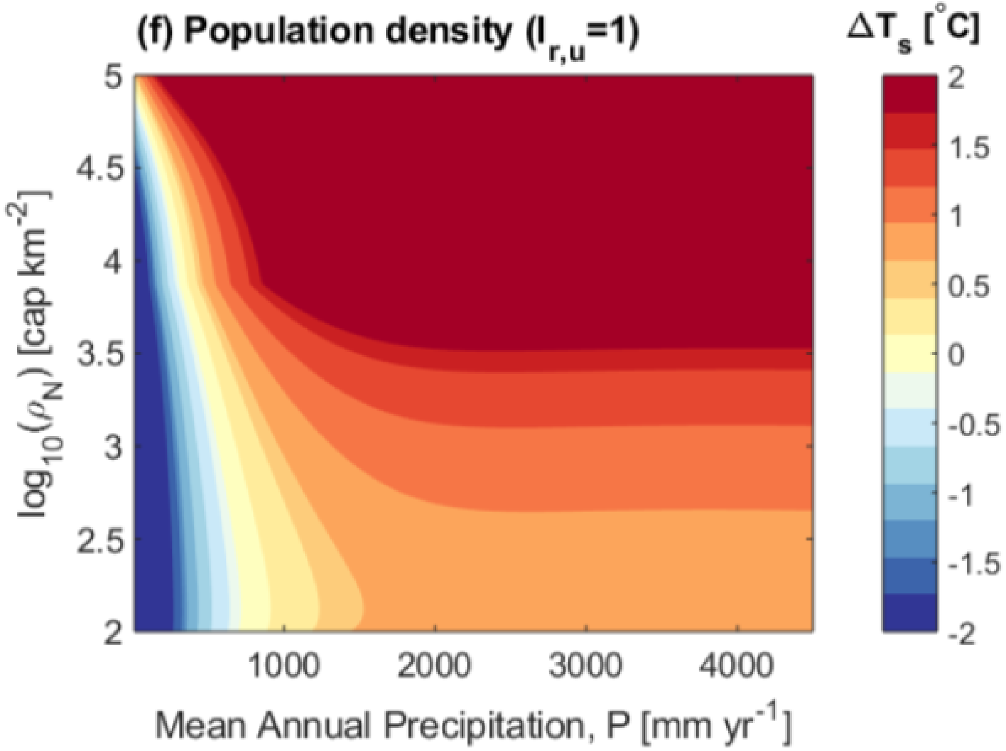


$I_u = 1$

3. 2 Heat Mitigation Strategies --- decreasing density (ρ_N)



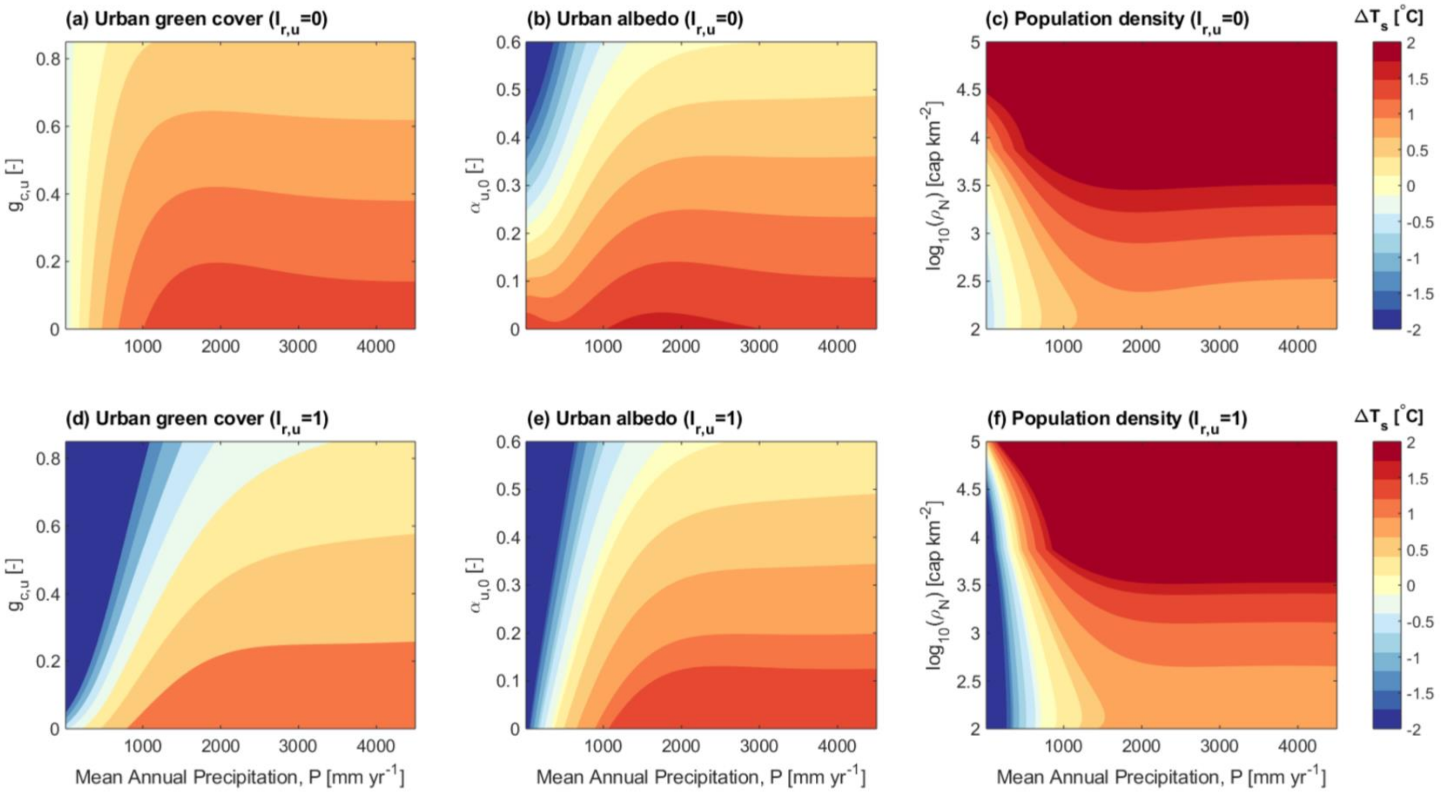
$I_u = 0$



$I_u = 1$

3. 2 Heat Mitigation Strategies --- A sensitive analysis

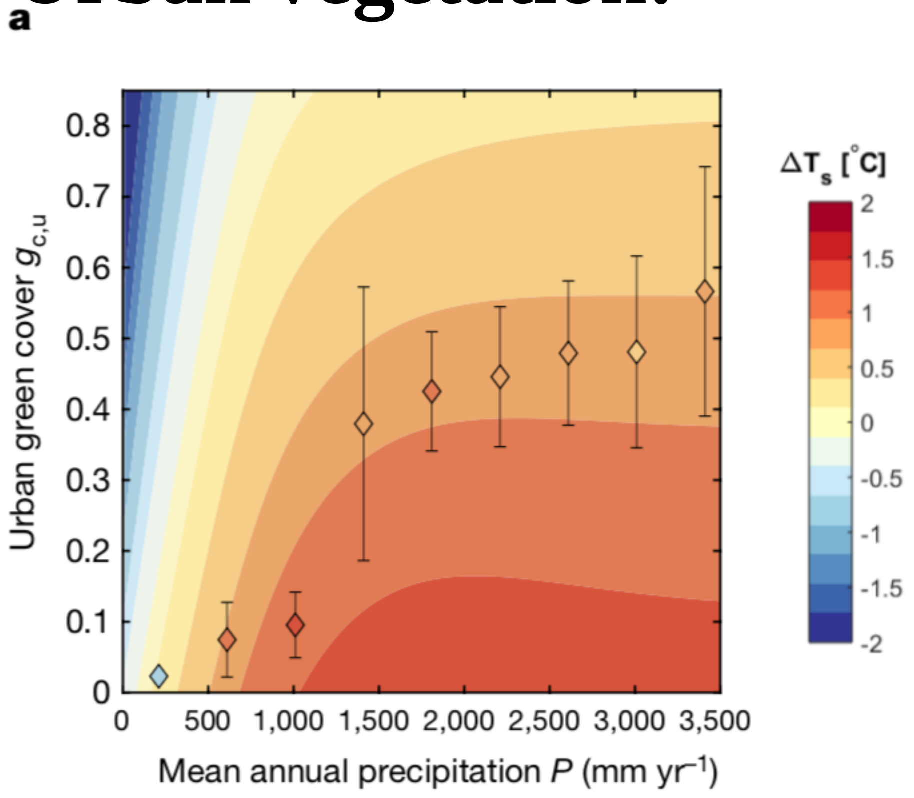
- **Increasing green space** ($g_{c.u}$), **increasing albedo** ($\alpha_{u.0}$), or **decreasing density** ($\boldsymbol{\rho}_N$)



- **Cooling strategies** focused on **vegetation and albedo** are more effective in regions with ***P* < 1000 mm yr^{-1}** because it is difficult to achieve $\Delta T_s \leq 0.5^oC$ at higher precipitation regimes, but it is maximized in arid regions where ΔT_s can be mitigated by irrigation.

3.3 Climate-sensitive urban planning

A. Urban vegetation:



- Urban vegetation: reduced pollution, improved health, recreation, biodiversity, shading, carbon sequestration etc.

- It is safe to state that heat mitigation strategies in urban environments that experience large precipitation should focus on maximizing **shading and ventilation** rather than **evaporative cooling**.

3.3 Climate-sensitive urban planning

B. Convective efficiency

- The aerodynamic properties of cities also help regulate the intensity of UHIs. ----- how complex, non-uniform, urban geometries influence the exchange of heat and momentum at the land surface **is still a subject of open research**.

C. Albedo

- Albedo management is also a viable option to reduce warming at the city scale. ------ given the seasonality of urban warming, albedo modifications can promote winter cooling and increase energy demand, especially in cold regions.

4. Conclusions

- Introducing a coarse-grained model that links population, background climate and UHI intensity：
  - A nonlinear increase in ΔT_s with precipitation that is controlled by water or energy limitations on evapotranspiration and that modulates the scaling of ΔT_s with city size.
- Coarse-grained model: only depending on mean annual precipitation and city population

Coarse-grained model ⟷ High-resolution simulations

4. Conclusions

- The direct implication of these nonlinearities is that mitigation strategies aimed at **increasing green cover and albedo** are more efficient **in dry regions**, whereas the challenge of cooling tropical cities will require innovative solutions.

Thank you