NCAR | COMMUNITY EARTH SYSTEM MODEL

The Grainger College of Engineering
Civil & Environmental Engineering

Advancing urban representation in CESM to understand urban climate at large scales

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&

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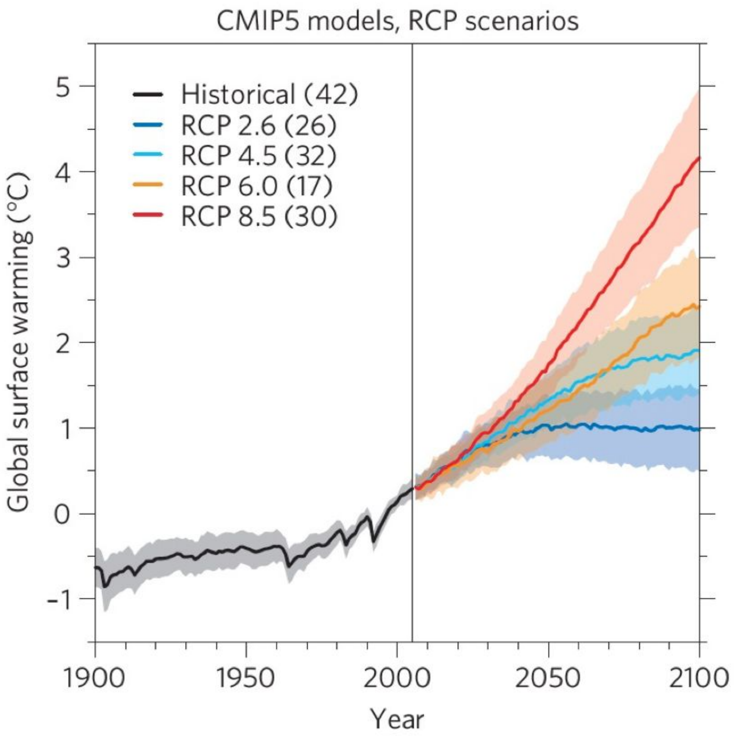
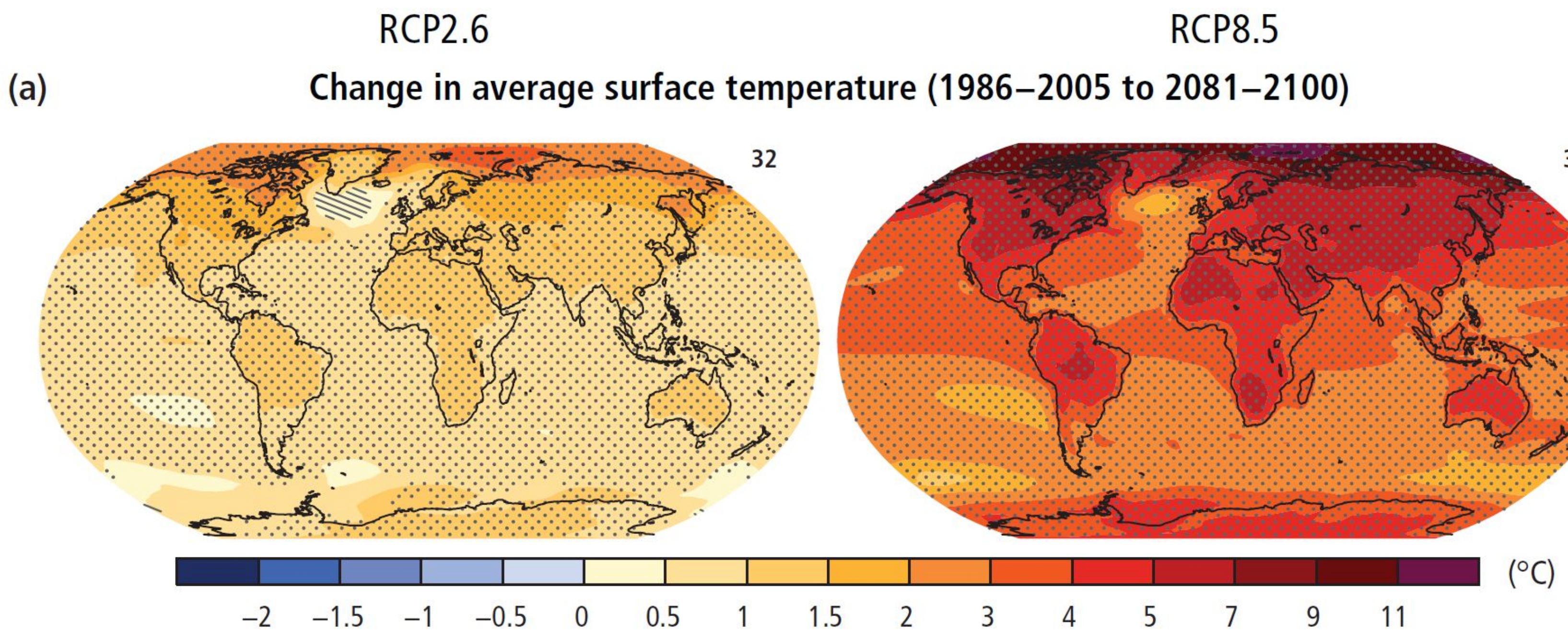
CESM Land Model Working Group Winter Meeting 2024

Global “surface” climate projections



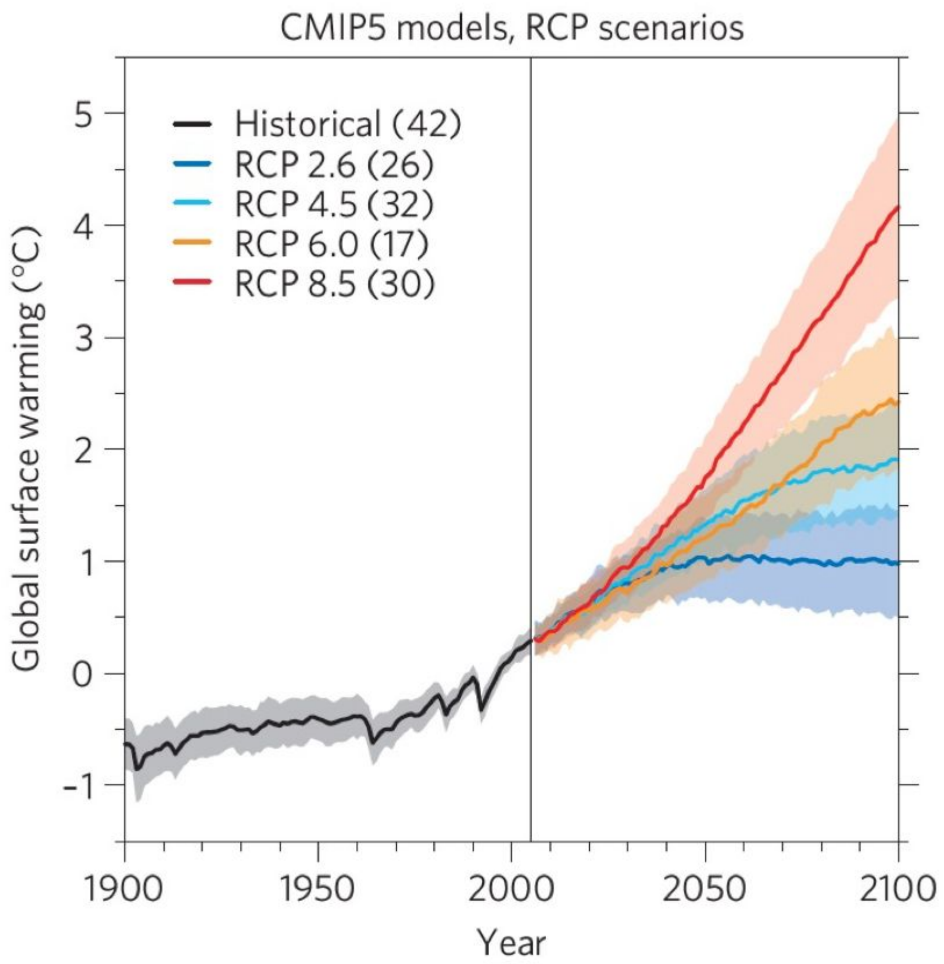
Knutti & Sedlacek, *Nat. Clim. Change* 2013



IPCC AR5

Are these modeled results “good” for urban areas?

Nearly all large-scale Earth system models lack an urban representation!

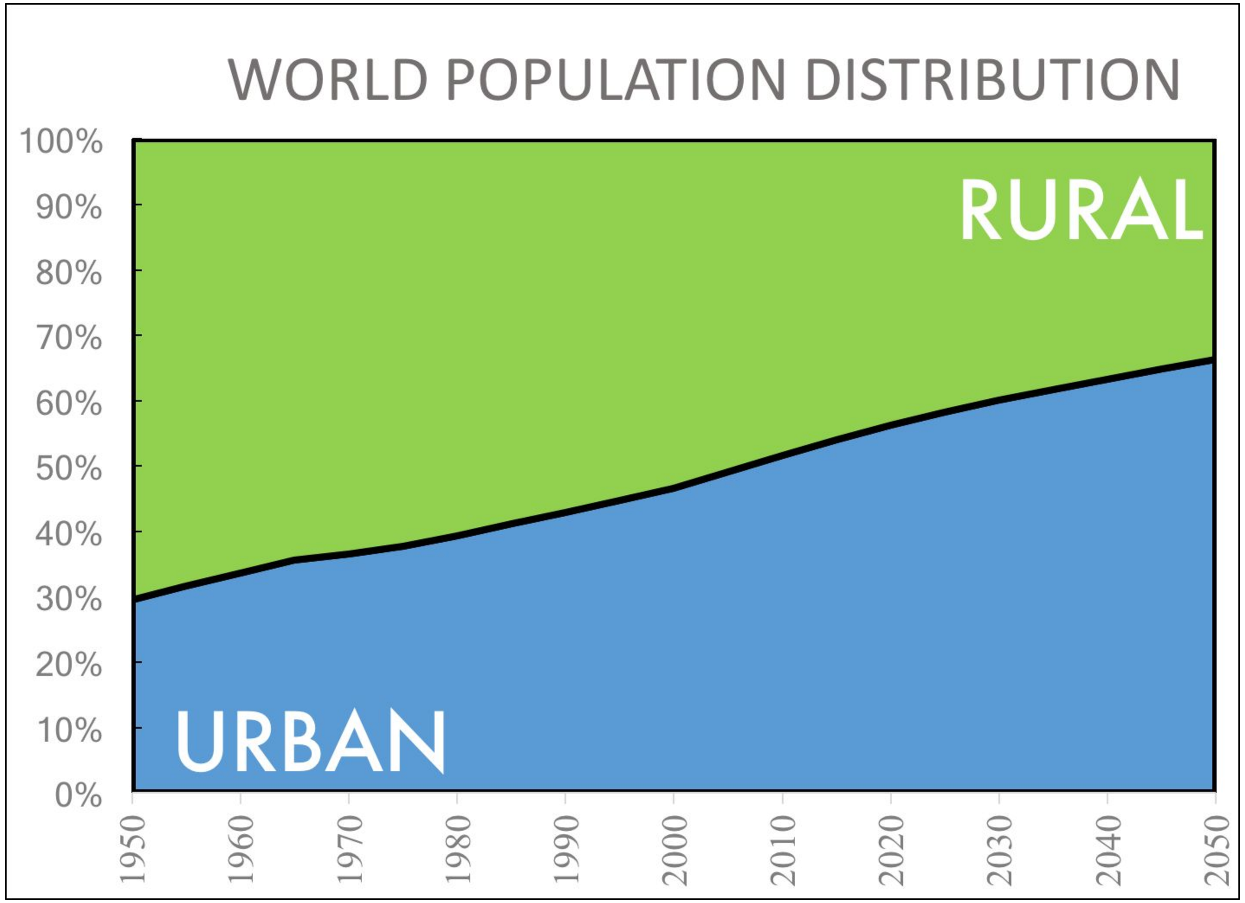


Traditional projections of "global surface climate" are essentially global "non-urban" surface climate.

Human-perceived impacts

2-3 %
of Earth's land surface

>50 %
of world population



Source: UN HABITAT


C F

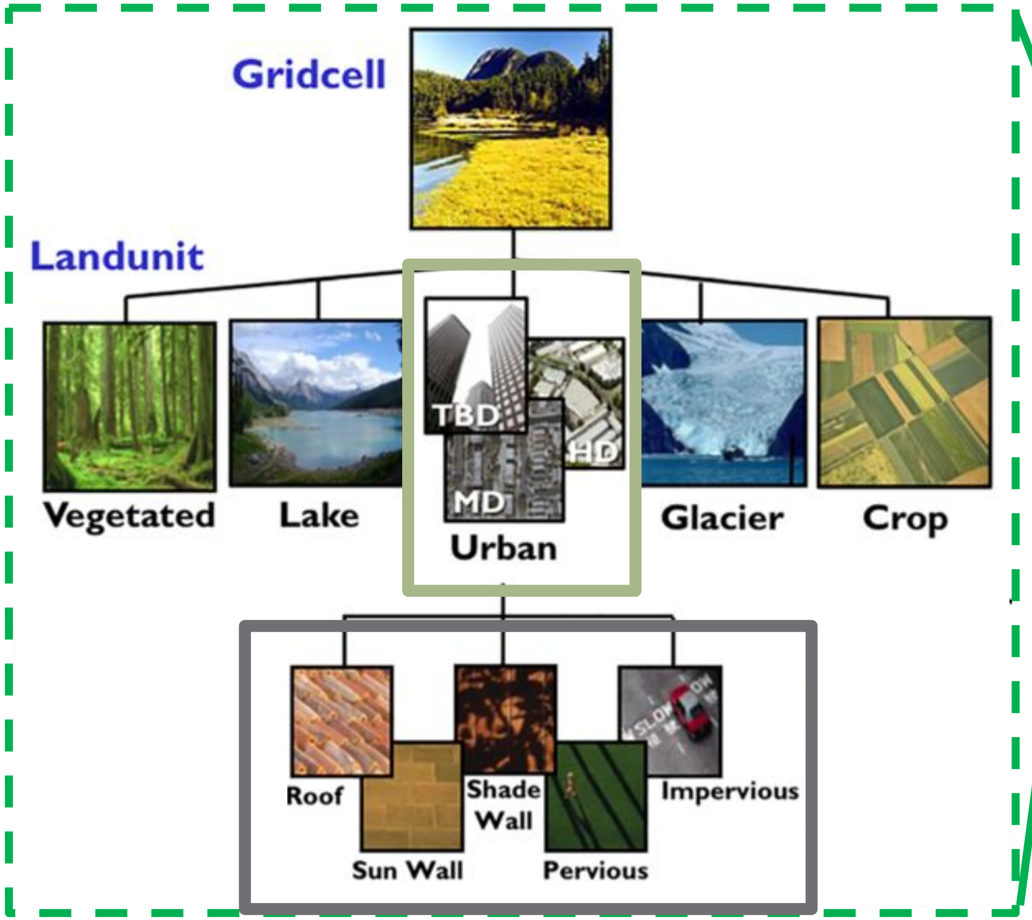

Climate-driven urban risks will worsen in the future because of …

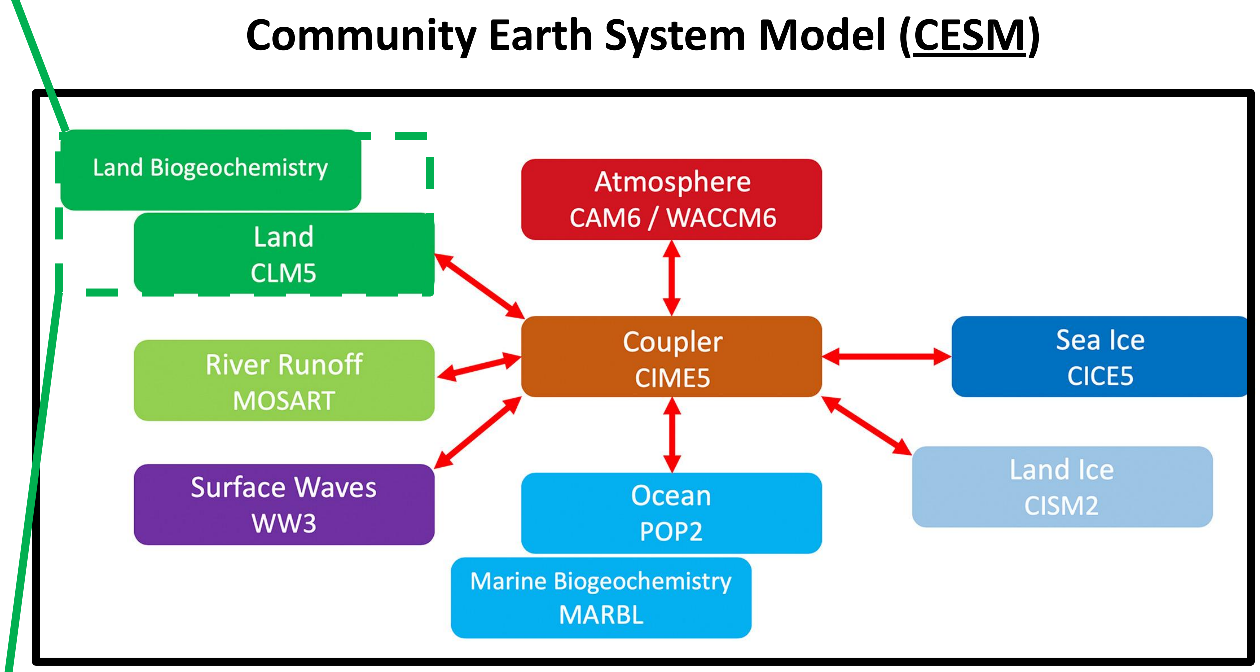
Urban development

+

Climate change

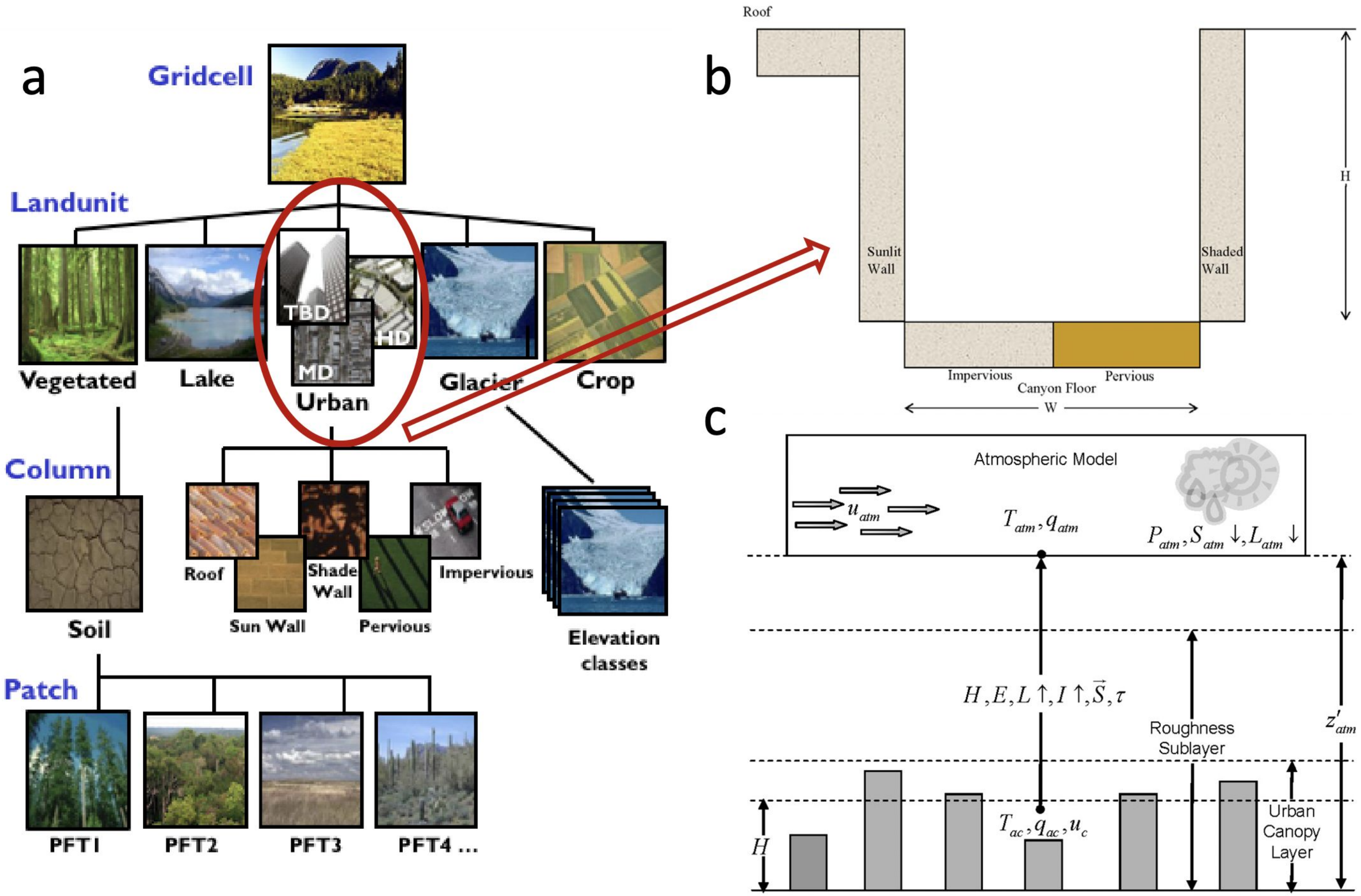
Urban representation in CESM





Lawrence et al. (2019), Danabasoglu et al. (2020)

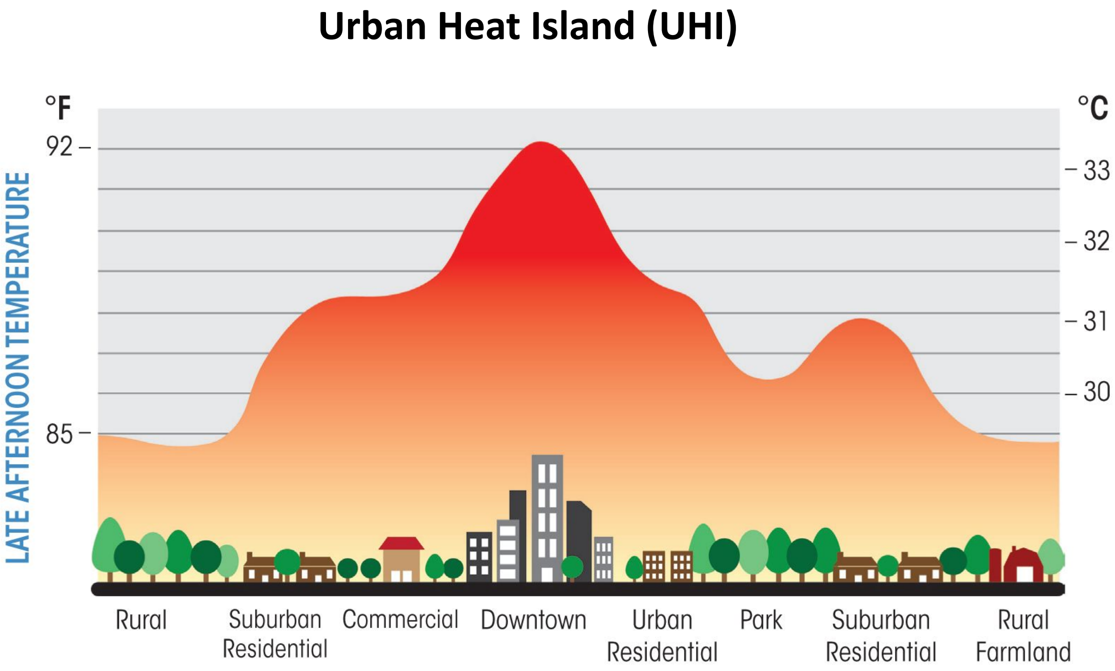
Urban representation in CESM

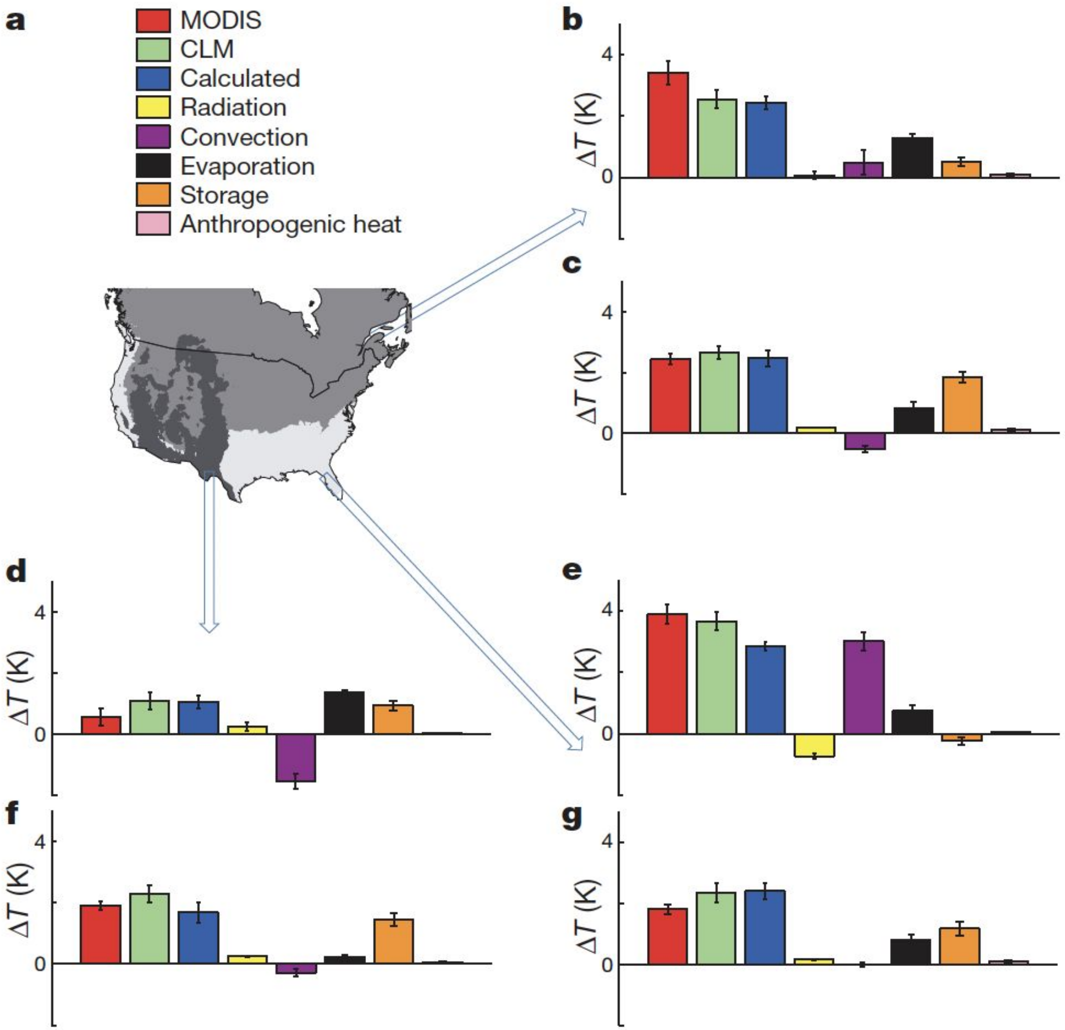


Source: http://www.cesm.ucar.edu/models/clm/human.html

Understanding urban heat at large scales

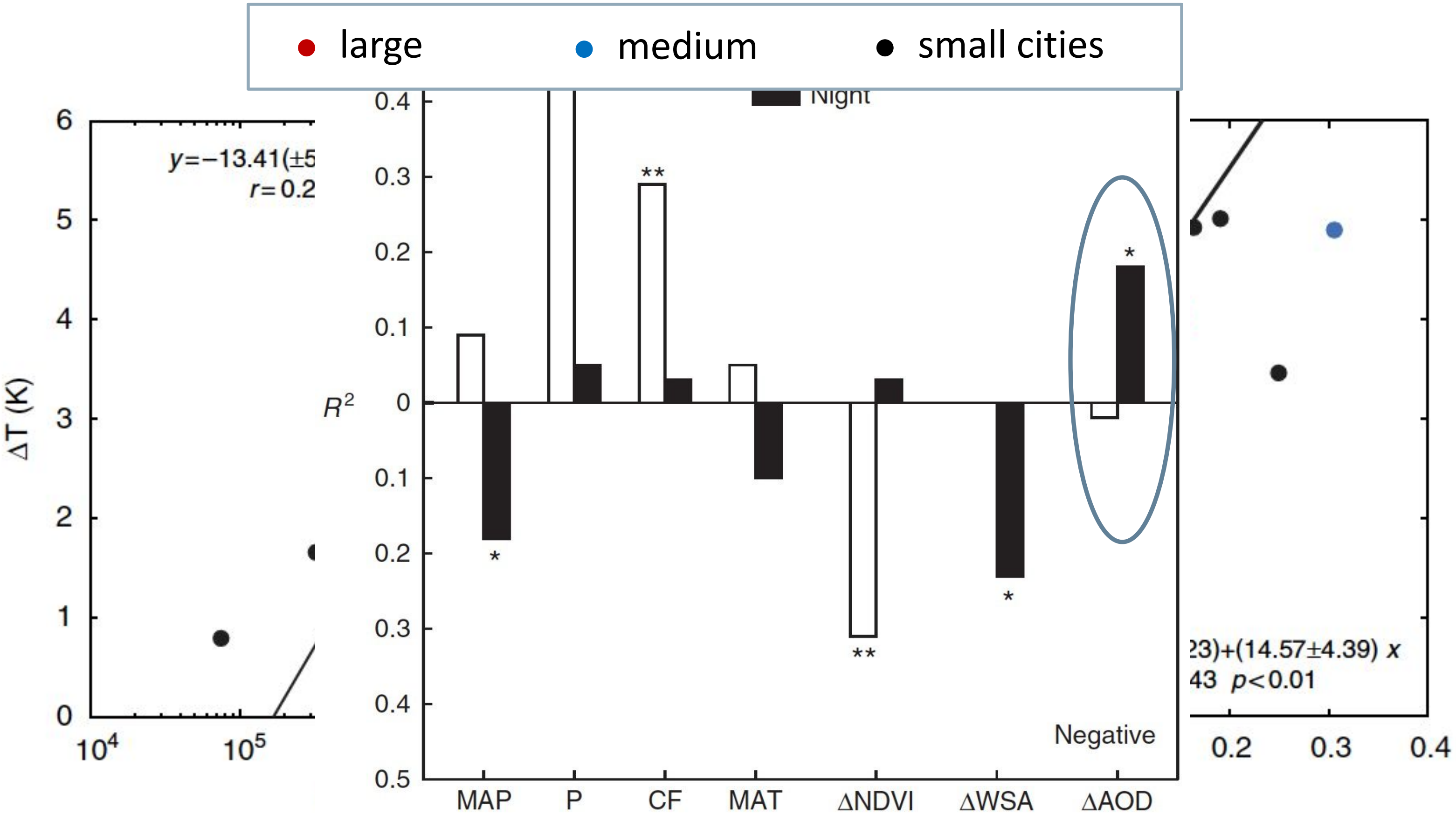
Urban heat island





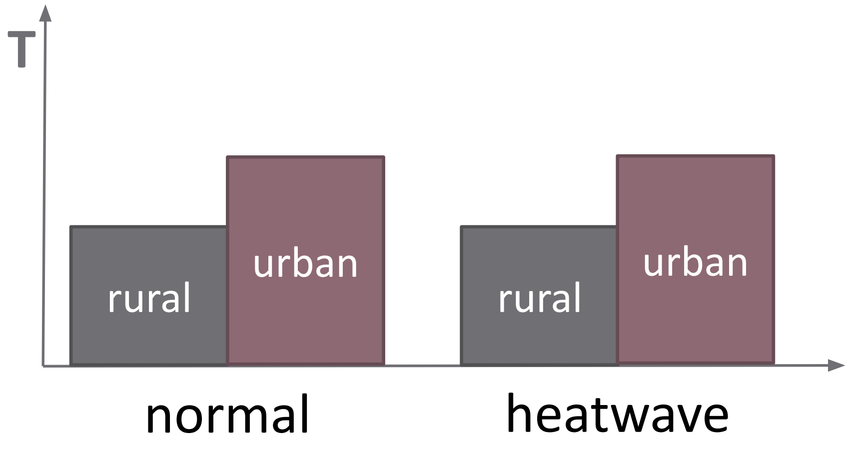
Zhao et al. *Nature* 2014

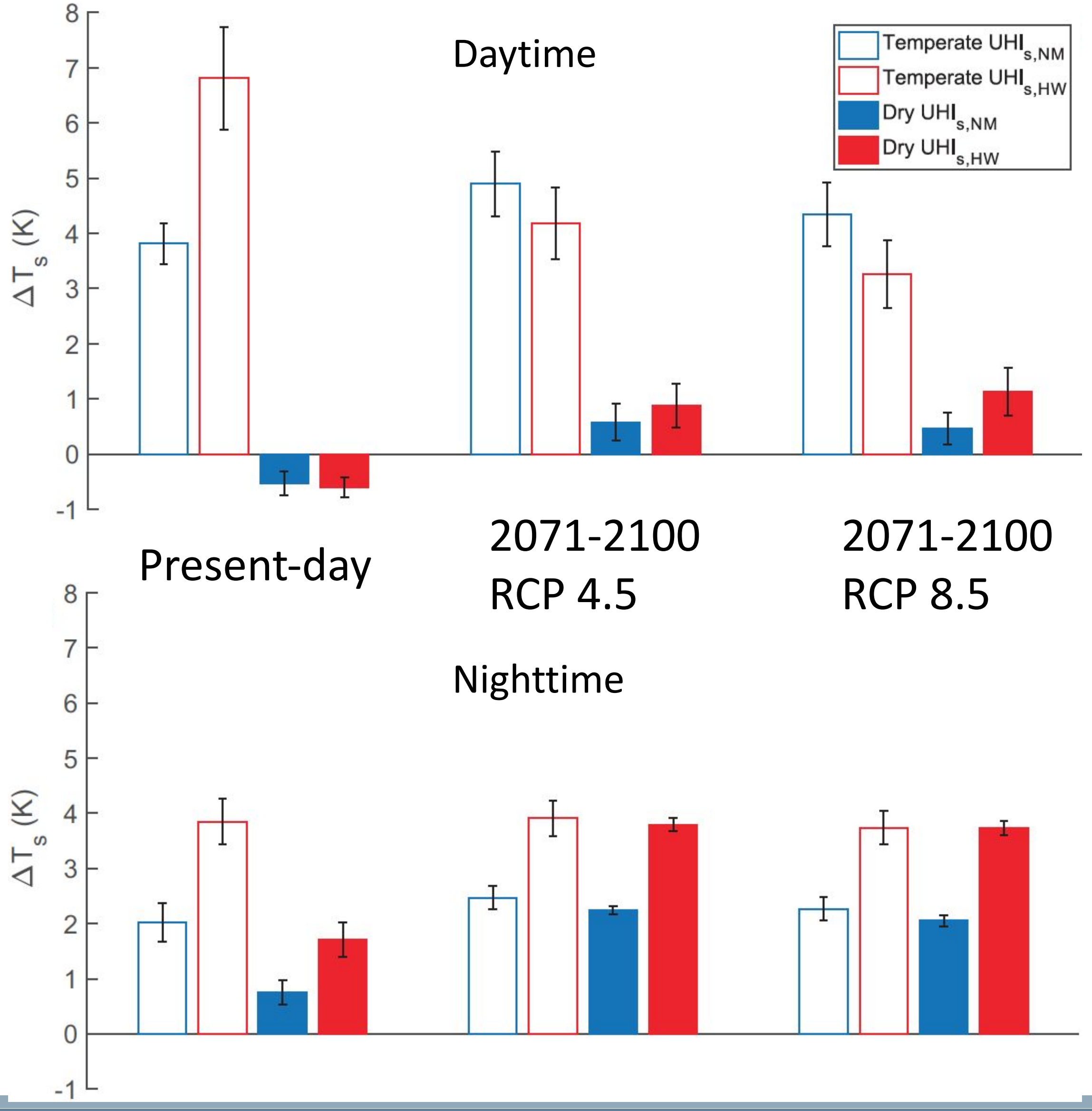
UHI interacts with air pollution



Cao et al. *Nature Comm.* 2016

UHI interacts with extremes





Zhao et al. *Env. Res. Lett.* 2018

Can we provide robust multi-model *urban* projections?

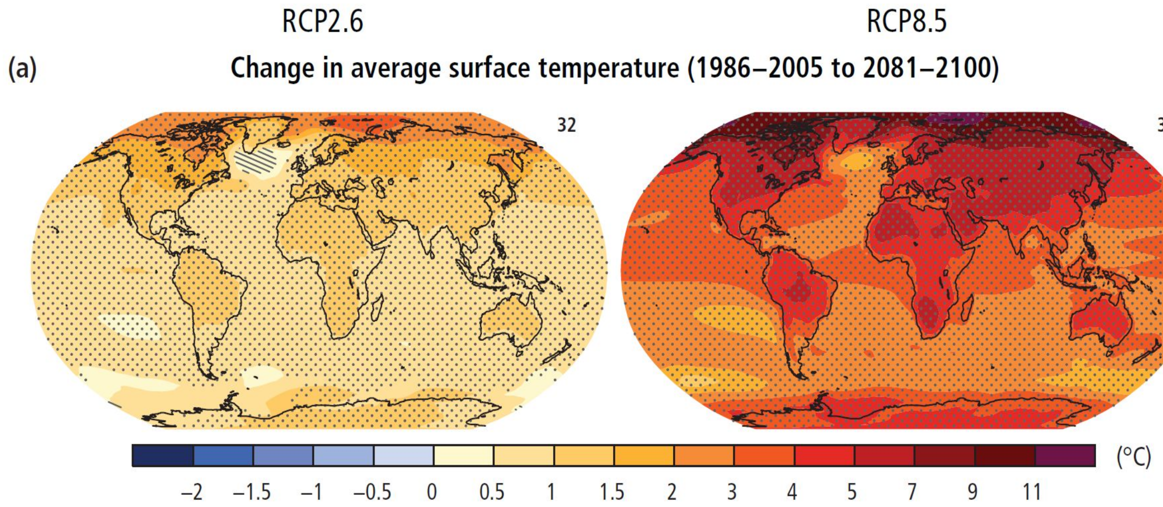
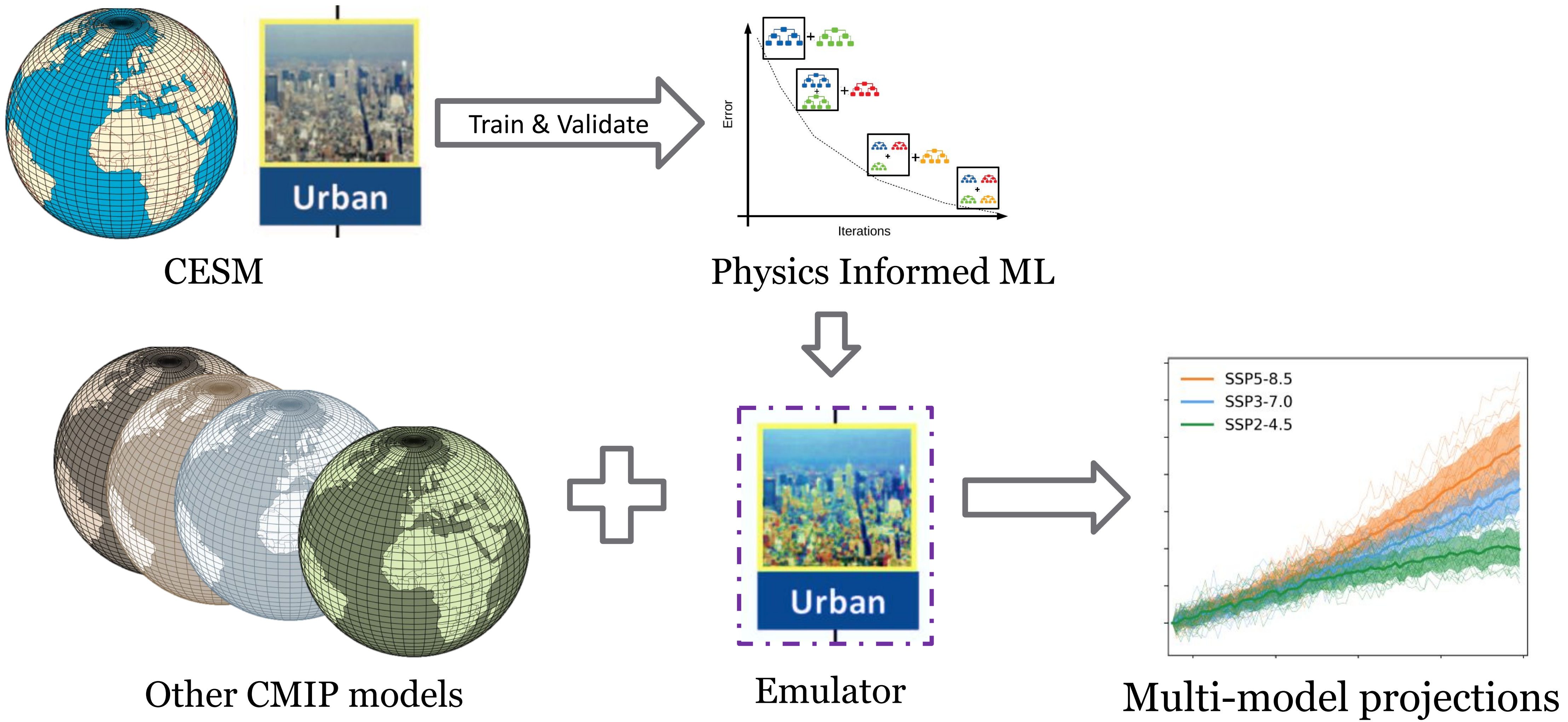


Figure SPM.7 | Change in average surface temperature **(a)** and change in average precipitation **(b)** based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. The number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability. *{2.2, Figure 2.2}*

Source: IPCC 2014, and Knutti & Sedlacek, *Nature Climate Change* 2013

An urban climate emulator framework



Robust projections of urban warming

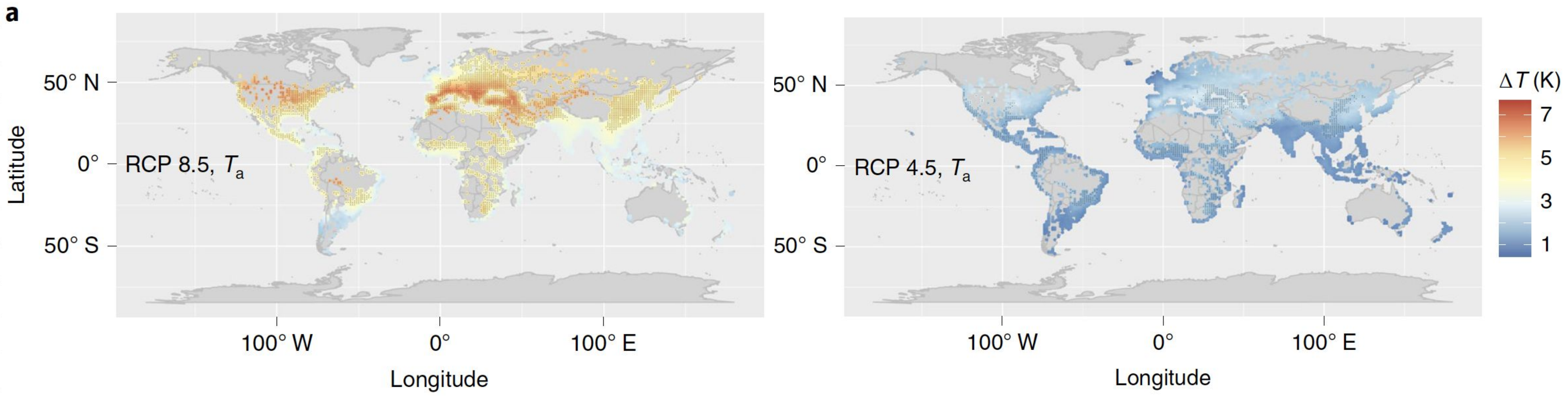


Figure: Multi-model ensemble mean urban warming for JJA under RCP 8.5 and RCP 4.5. Stippling indicates significant change ($\Delta T \geq 4$ K under RCP8.5 and $\Delta T \geq 1.5$ K under RCP45) with high inter-model robustness (SNR > 2.5).

Zhao et al. *Nature Climate Change* (2021)

Future urban heatwaves

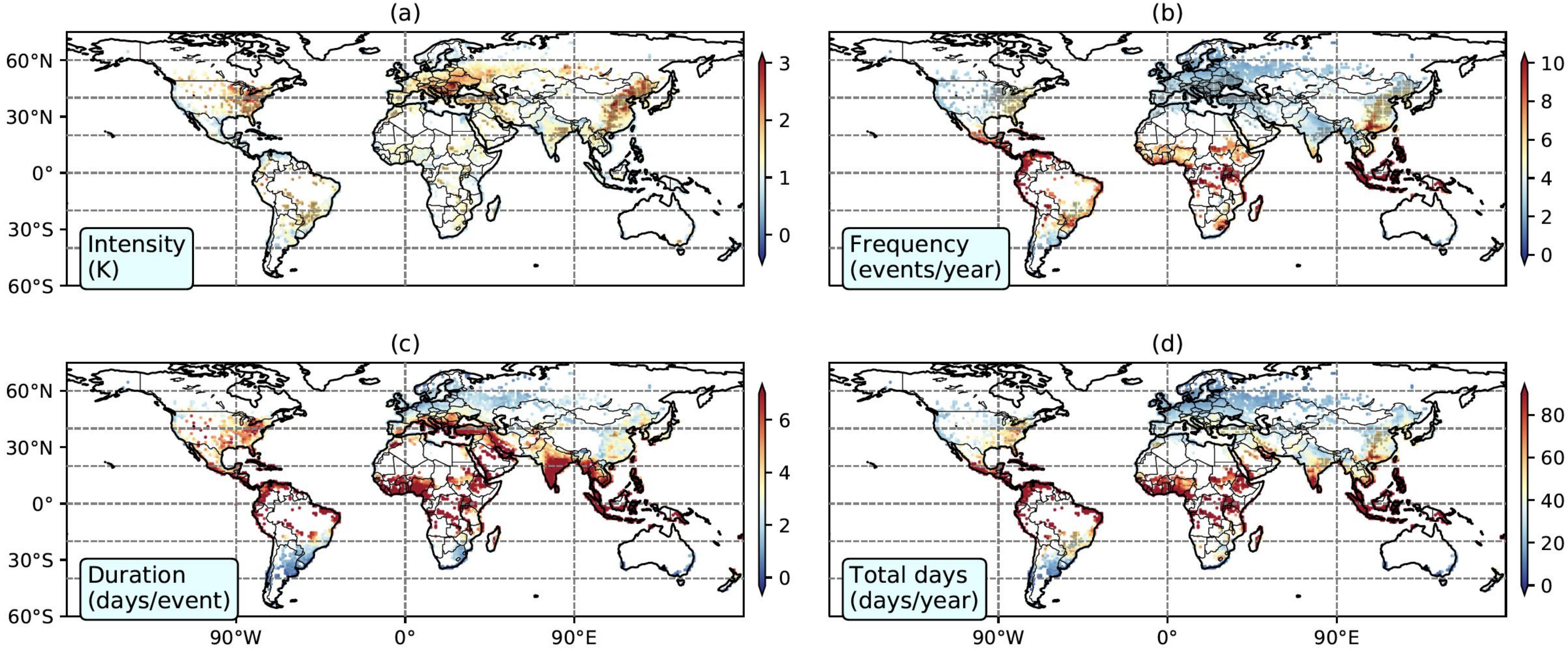


Figure: Multi-model ensemble mean change in average UHW intensity (K), frequency (events per year), duration (days per event), and total days (days per year) in 2061–2070 relative to 2006–2015. Stippling indicates substantial change (intensity > 1.5 K) with high inter-model robustness (SNR > 2.0).

Zheng et al. *Nature Comm.* 2021

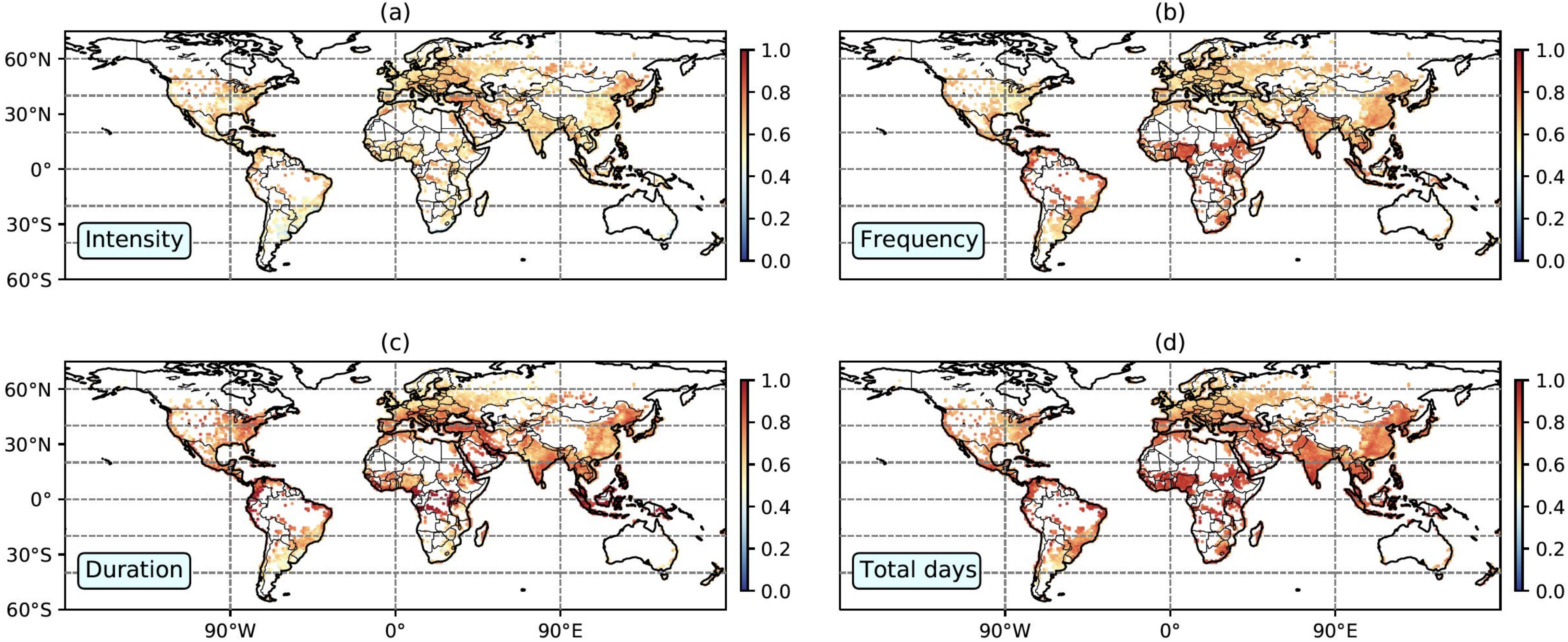


Figure 3. Relative contribution of the model structural variability in UHW projections. Each colored point represents a decadal mean structural uncertainty fraction (SUF) defined as $\frac{\sigma_{CMIP}}{\sigma_{CMIP}+\sigma_{CESM}}$

Source: Zheng et al. *Nature Comm.* 2021

Grey-swan urban heatwaves

Seemingly unlikely
0.01% UHW

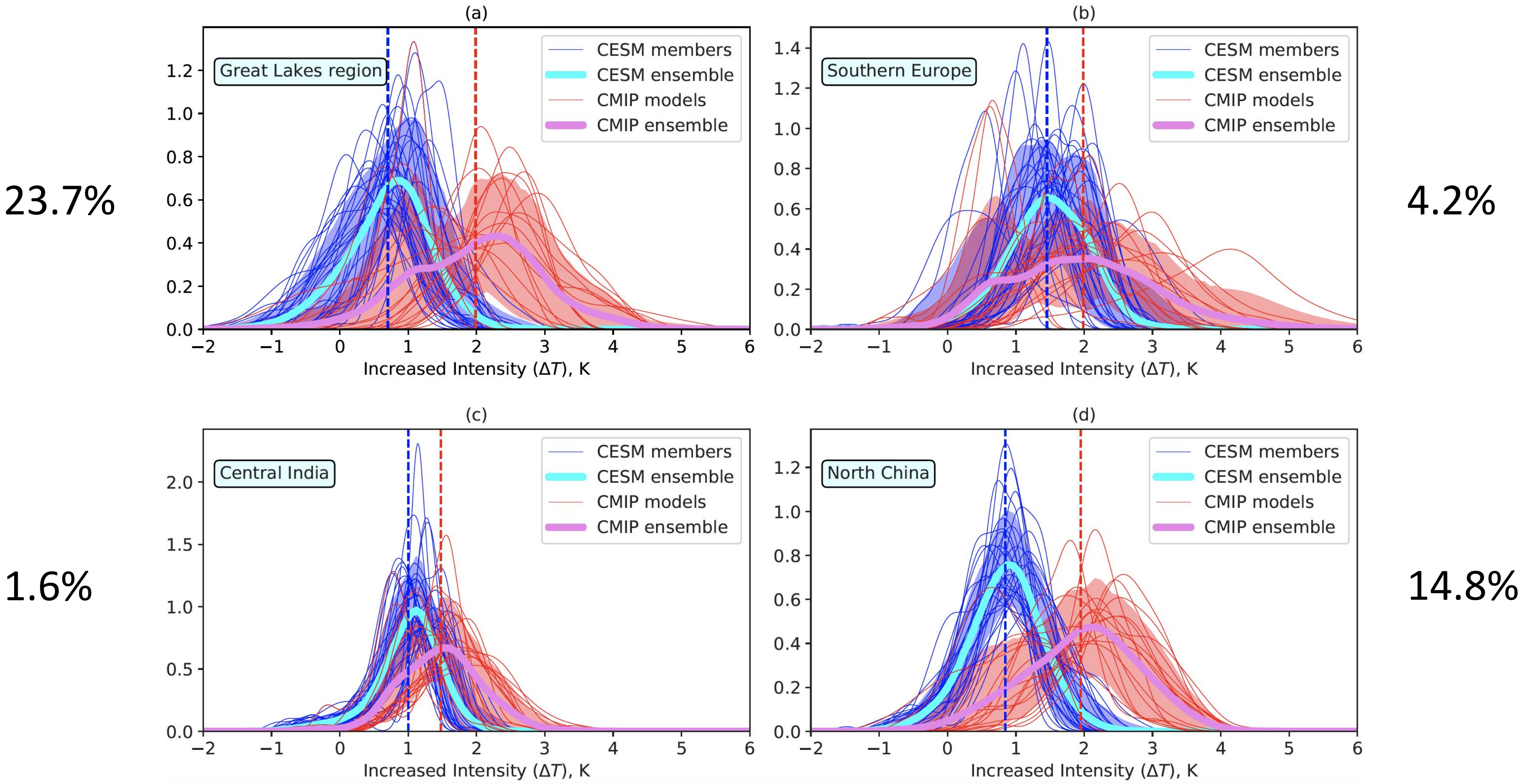


Figure: Spatial distribution of changes in urban heat waves intensity by 2061 – 2070. The thick lines mark the CMIP5 multi-model mean (thick violet lines) and CESM-LE multi-member mean (thick cyan lines).

Zheng et al. *Nature Comm.* 2021

Urban humid heat

Urban warming and "drying"

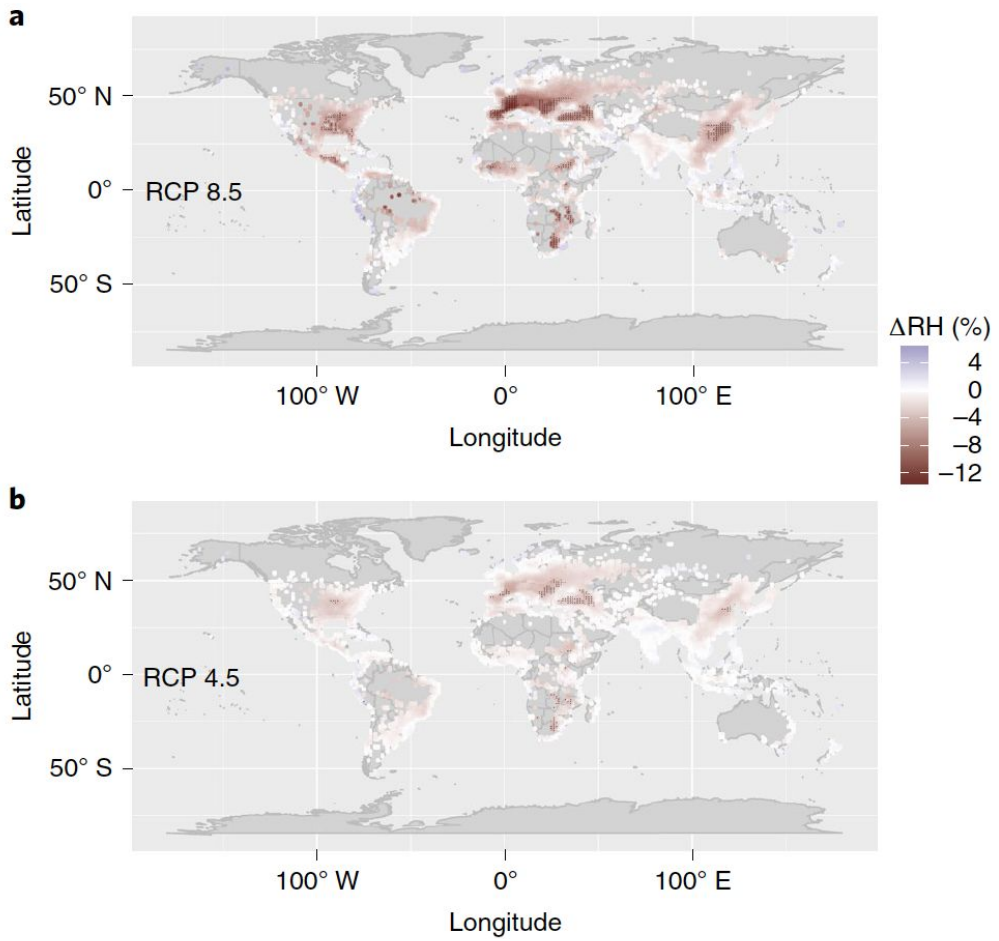
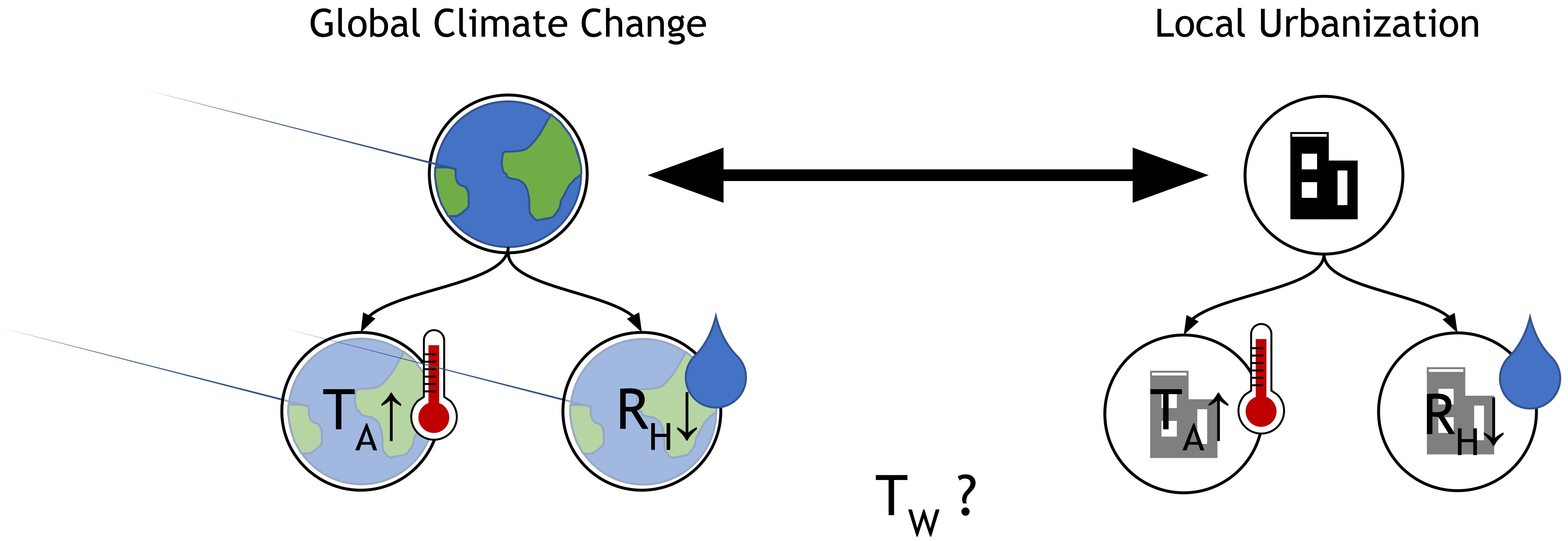


Fig. 4 | Multi-model mean urban relative humidity change for JJA. a,**b**, Seasonal mean urban RH changes between 2006–2015 and 2091–2100 under RCP 8.5 (**a**) and RCP 4.5 (**b**). Stippling indicates substantial change (abs(ΔRH) > 5% under RCP 8.5 or abs(ΔRH) > 2.5% under RCP 4.5) with high inter-model robustness (SNR > 1).

Zhao et al. *Nature Climate Change* (2021)

Urban warming and "drying"

Both climate change and urbanization tend to result in **higher temperatures and lower humidity.**



Urban wet-bulb heat island

Energy balance of web-bulb temperature $T_w + \frac{e_s^*(T_w)}{\gamma} = T_a + \frac{e_a}{\gamma}$ ⟶ $\Delta T_w = w_1 \Delta T_a + w_2 \frac{\Delta e_a}{\gamma}$

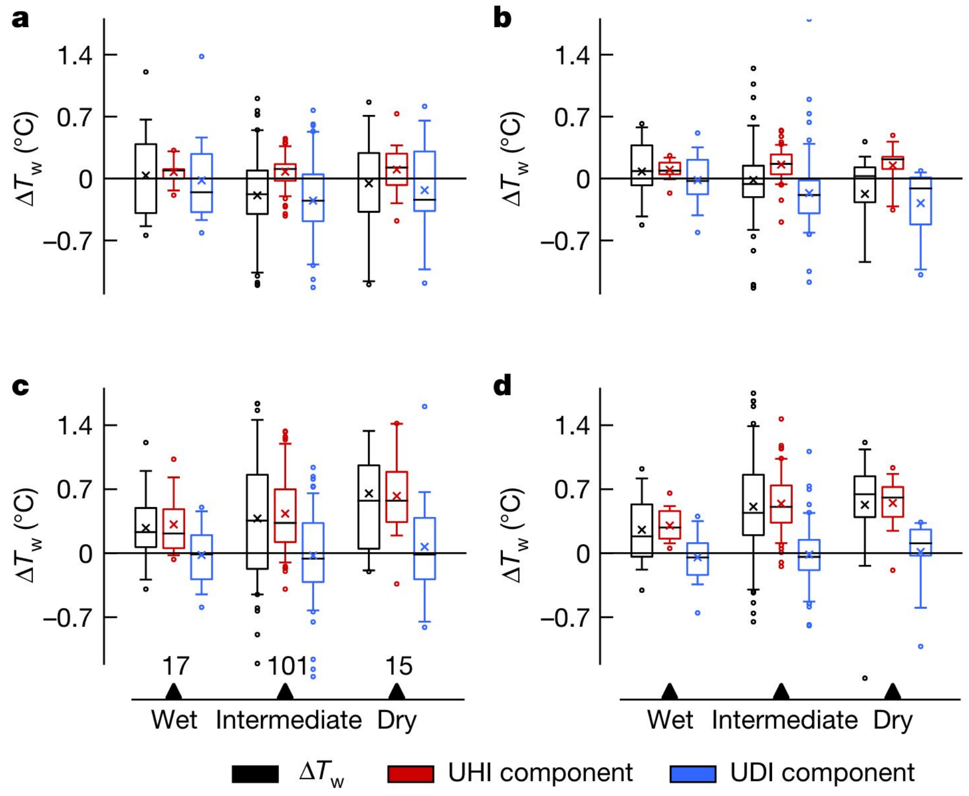


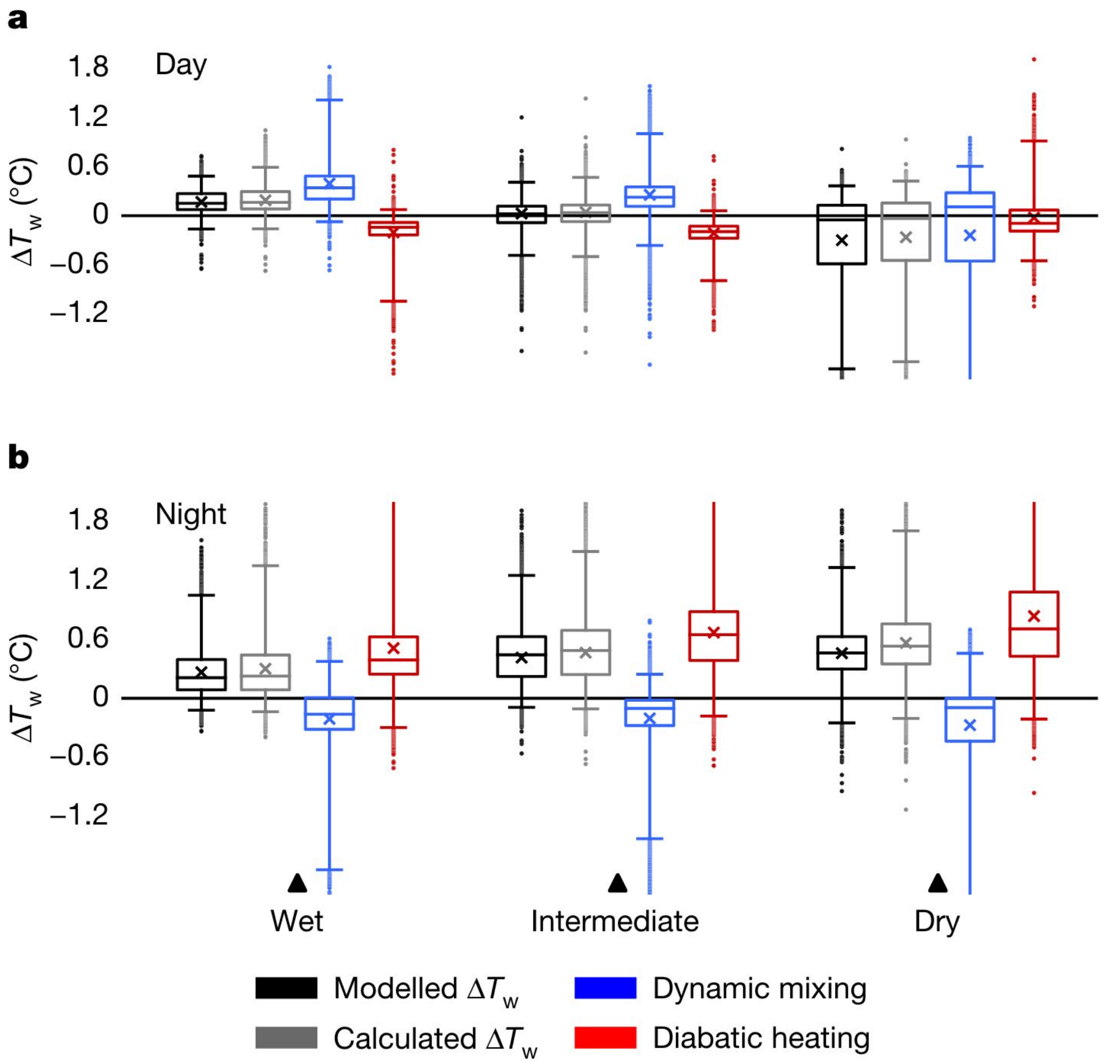
Fig. 1 | The urban wet-bulb island depends on time of the day and on climate wetness. a,**c**, Observed daytime (**a**) and nighttime (**c**) ΔT_w and its components. **b**,**d**, Modelled daytime (**b**) and nighttime (**d**) ΔT_w and its components. The model results are for grids corresponding to the urban–rural station pairs and from the same time periods. The box plots show the median (line), 25–75% range (box), 5–95% range (whiskers) and the mean value (cross). Station pair numbers are indicated in **c**.

Zhang et al. *Nature* (2023)

Urban wet-bulb heat island

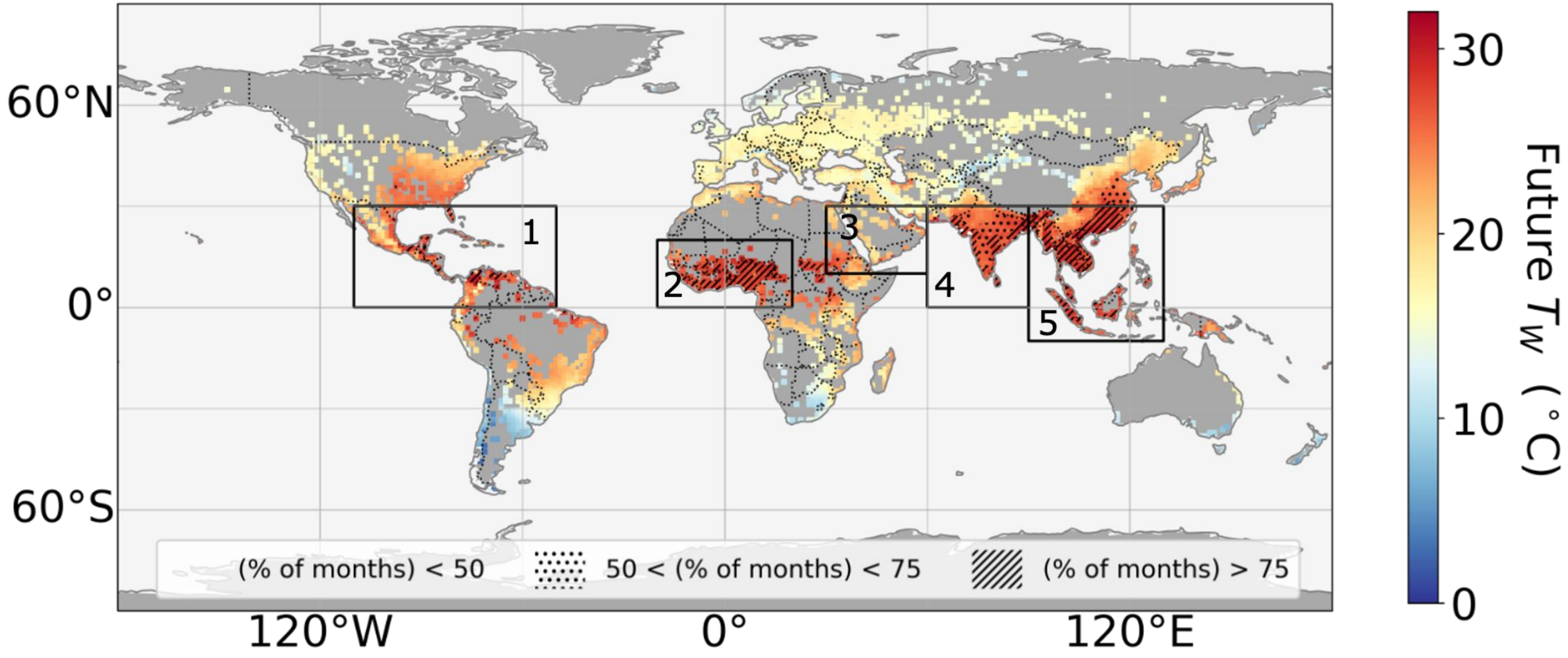
$$\Delta T_w = \frac{1}{\rho c_p(1+\Delta_w/\gamma)}[\Delta r_a(R_n+Q_A-G)+r_a\Delta(R_n+Q_A-G)]$$

Dynamic mixing Diabatic heating difference



Zhang et al. *Nature* (2023)

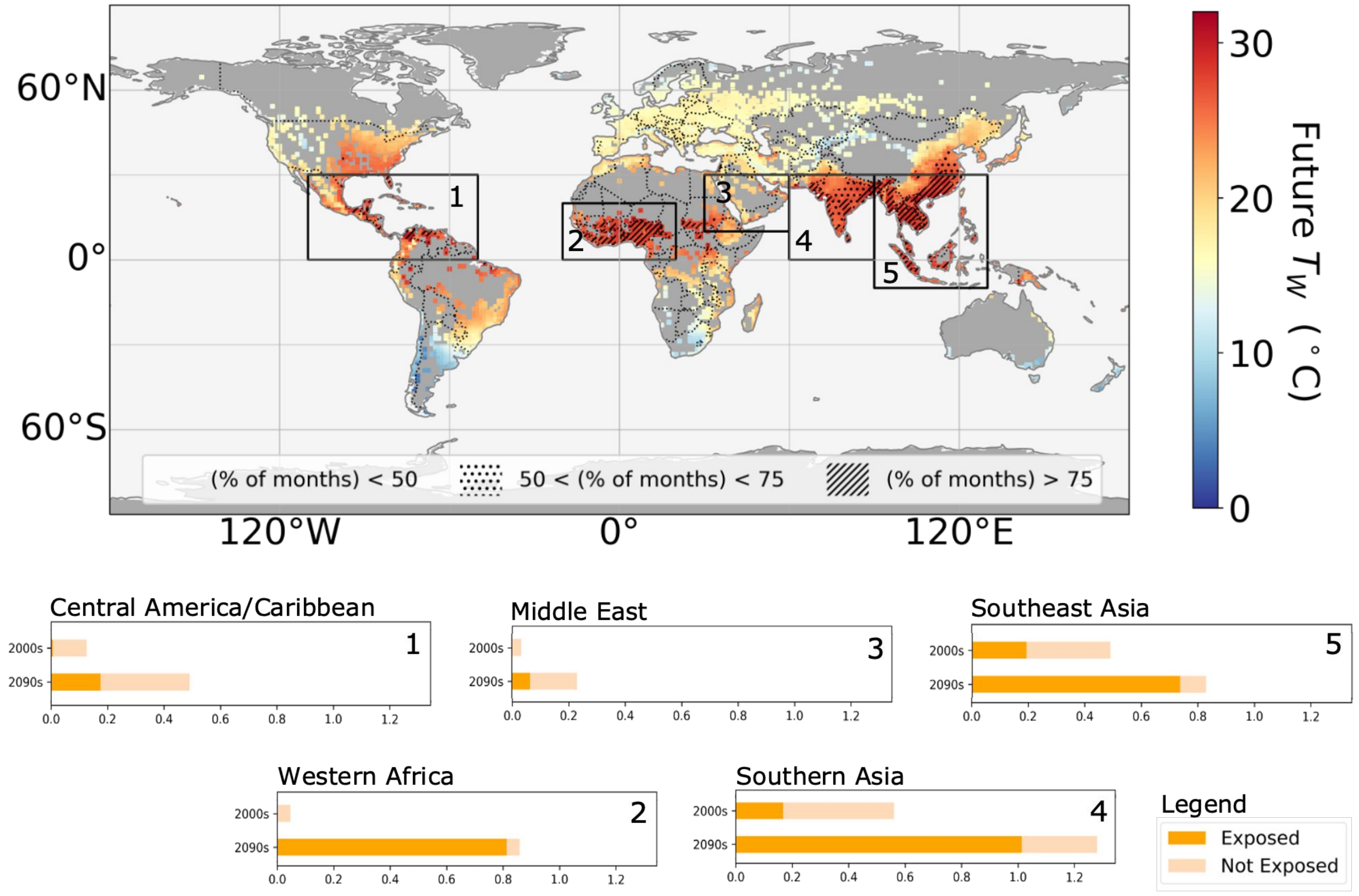
Urban humid heat increases globally, despite projected urban "drying". There is a tendency towards high urban humid heat in coastal, tropical urban areas – with potential for chronic heat stress.



Urban humid heat (June-July-August, JJA) in the 2090s under SSP3-RCP7

Yang et al. *Env. Res. Lett.* (2023)

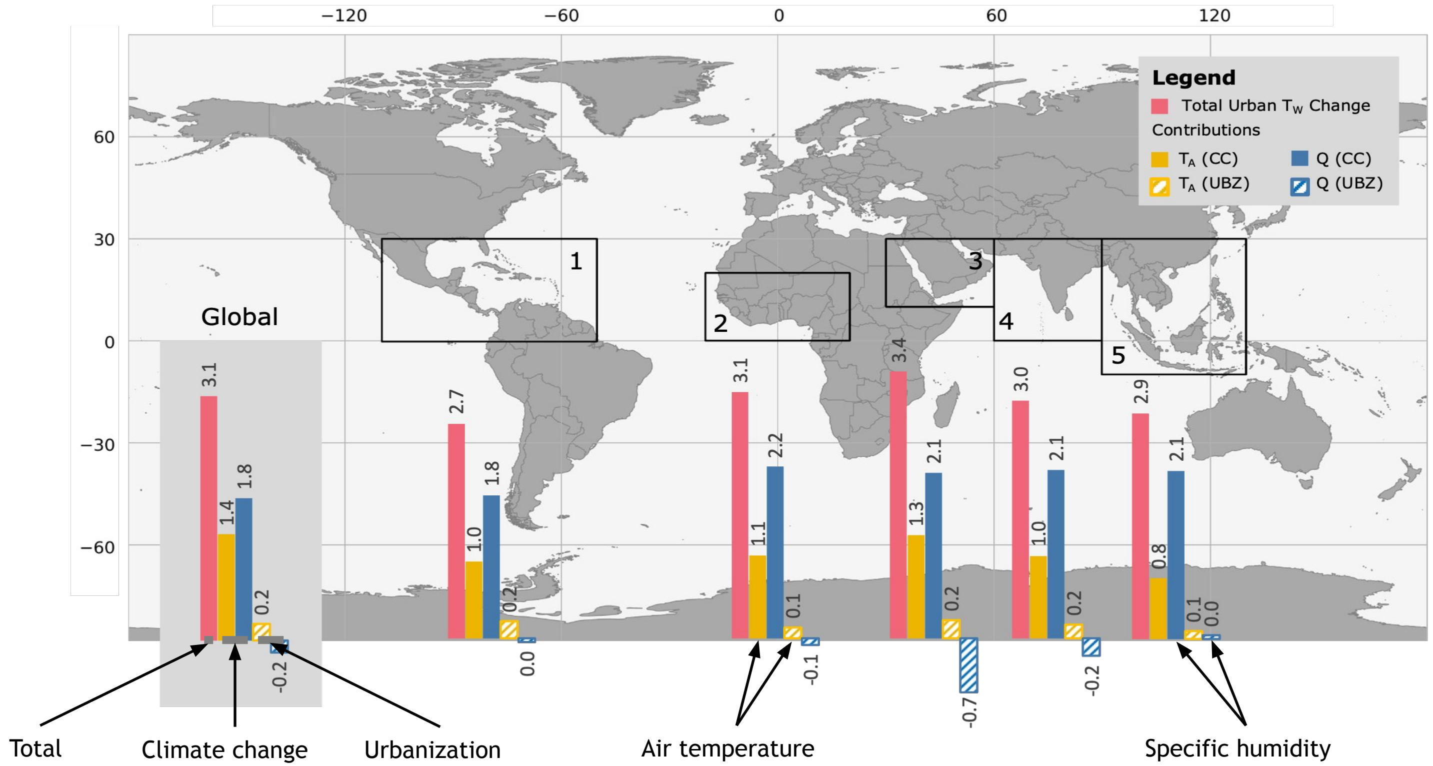
In some areas of the world, growth in urban population potentially exposed to chronic heat stress is faster than growth of the total urban population.



Growth in urban humid heat exposure under SSP3-RCP7

Yang et al. *Env. Res. Lett.* (2023)

The near-universal elevated urban humid heat stress is largely driven by climate change and the substantial resulting specific humidity increases.



Total and decomposed change in urban humid heat

Yang et al. *Env. Res. Lett.* (2023)

Globally-consistent, climate-driven dilemma to cooling through ***urban greenery***:
cities with greater (lower) atmospheric water availability tend to have lower (greater) cooling efficacy.

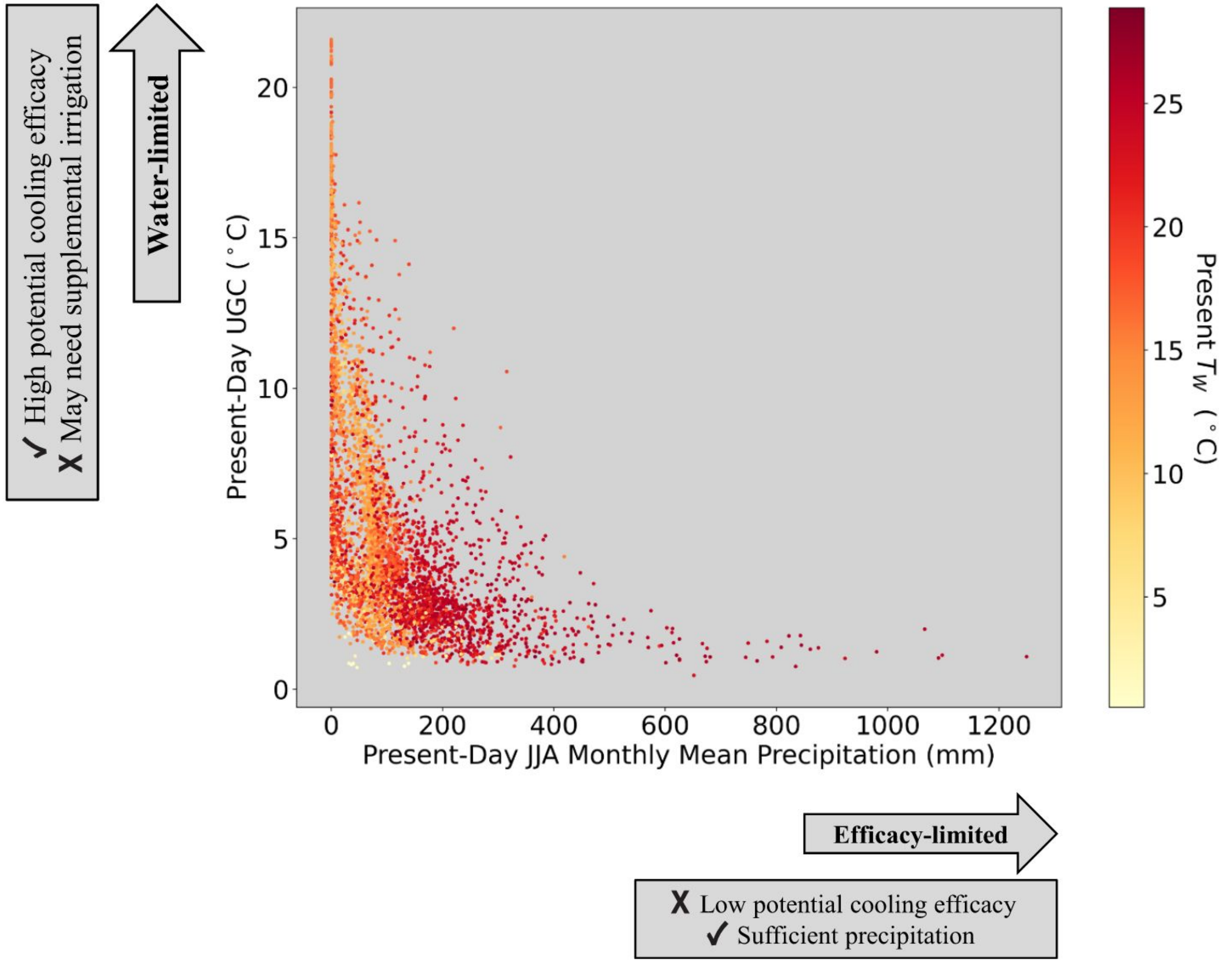


Figure 5. Irrigation needs and cooling efficacy of UGI at the start of the century (2000–2009). Irrigation needs and cooling efficacy are reflected through the proxies of precipitation and UGC, respectively. Precipitation and UGC are decadal mean urban JJA values. Colors indicate the decadal mean JJA urban T_W.

T_w: moist static energy

$$\Delta T_w = w_1 \Delta T_a + w_2 \frac{\Delta e_a}{\gamma}$$

Is urban green strategy really ***evaporative “cooling”***?

Yang et al. *Env. Res. Lett.* (2023)

Advancing urban representation in CESM

Key gaps and challenges

- Large urban underrepresentation in SOTA ESMs
- Globally consistent, reliable, and realistic urban surface property data
- Understanding and representing urban-scale processes and dynamics

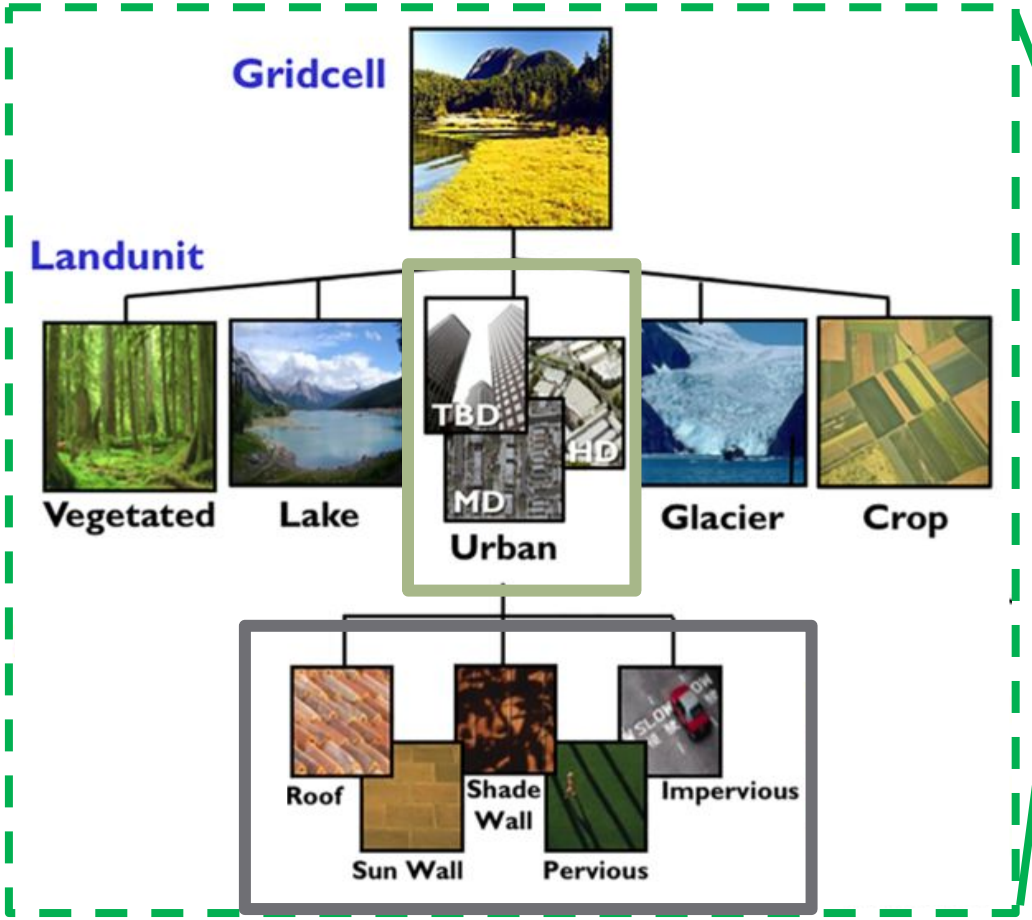
Data

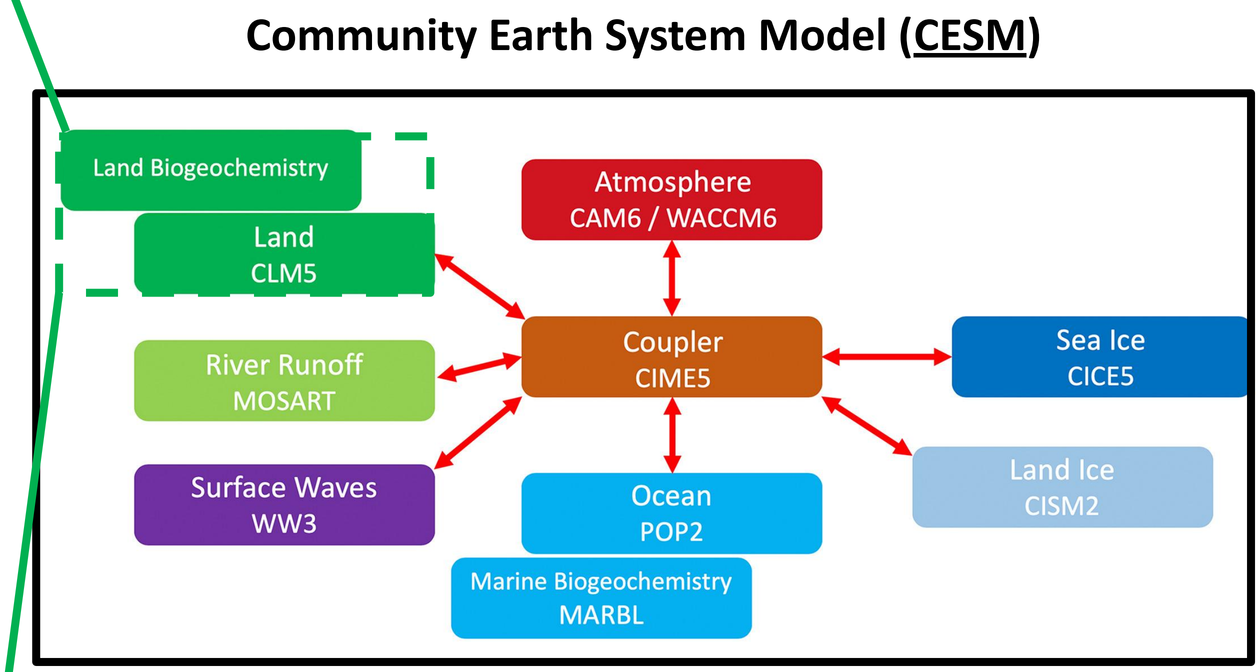
Science

Computing

1. Dynamic-urban CESM

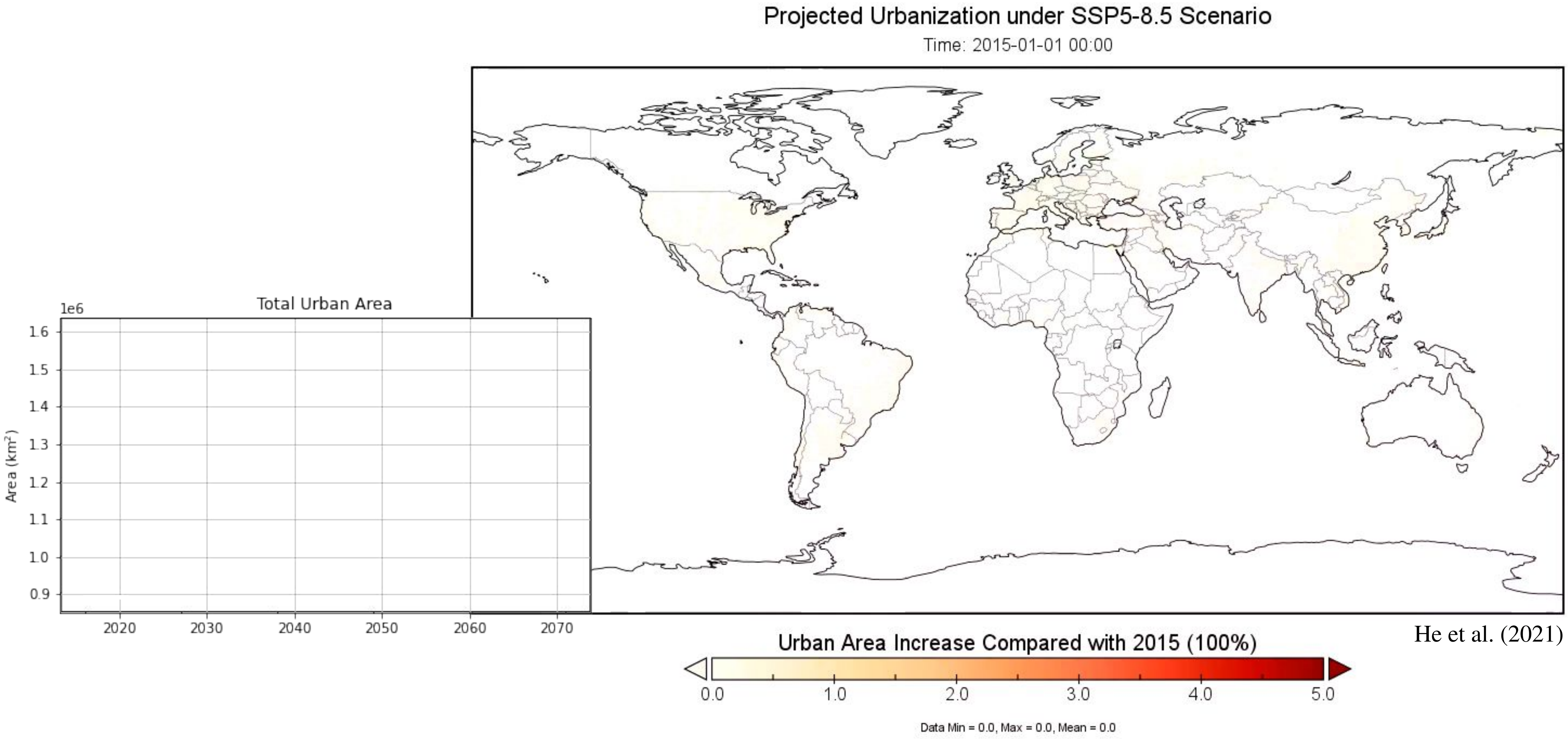
A critical limitation in current ESMs: static urban





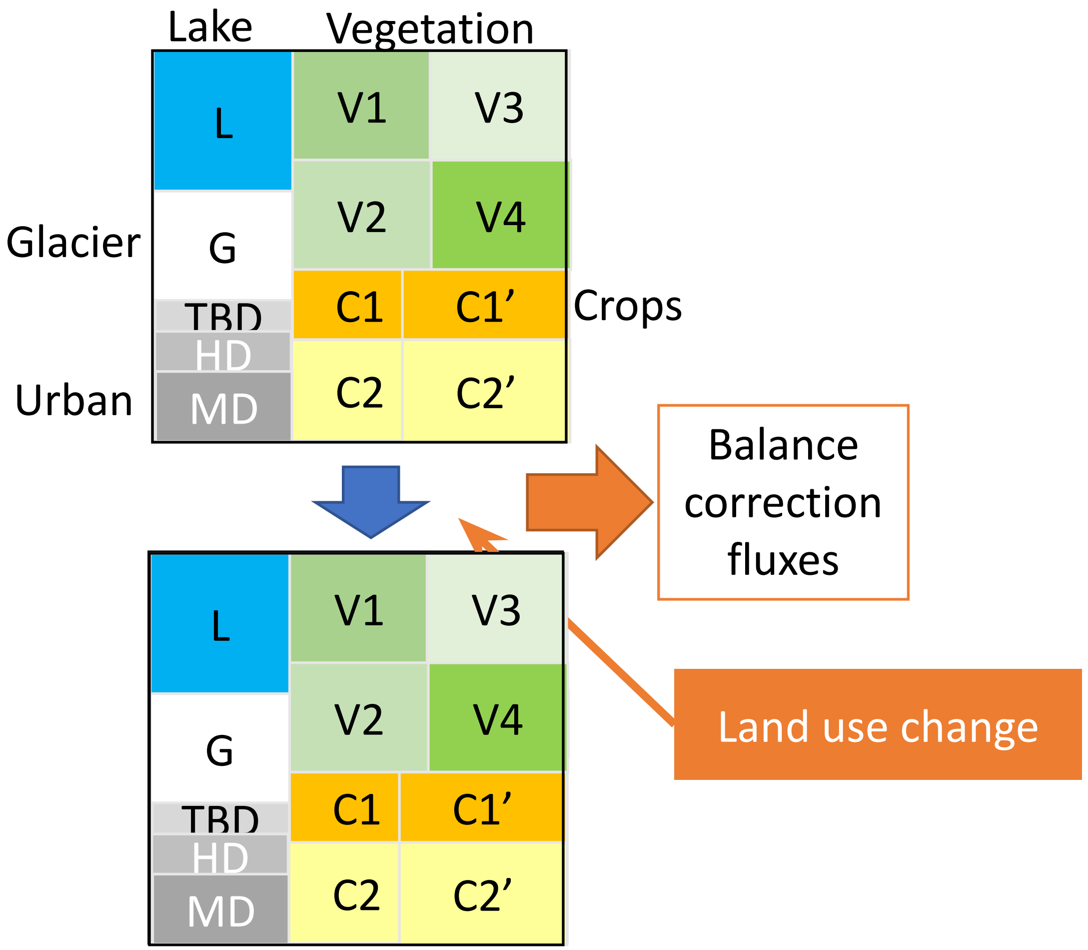
Source: Lawrence et al. (2019), Danabasoglu et al. (2020)

Rapid urbanization could have climate impacts at local scale and beyond



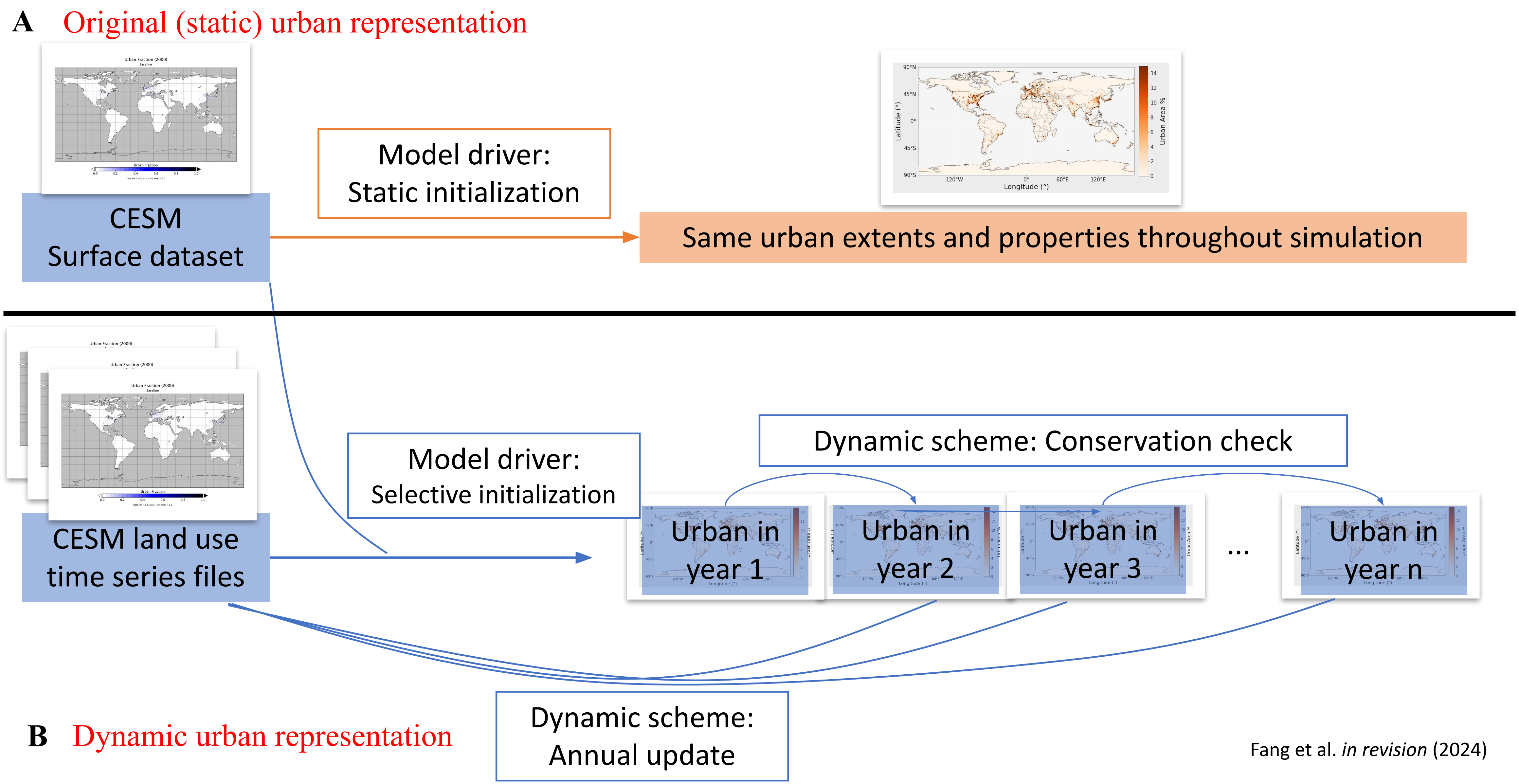
He et al. (2021)

A new dynamic urban scheme in CESM



Fang et al. *in revision* (2024)

Dynamic urban scheme in CESM



Fang et al. *in revision* (2024)

The new dynamic urban scheme opens up new opportunities

master ▾ CTSM / doc / ChangeSum   Go to file   History

billsacks Update ChangeLog   Latest commit 563ce93 24 days ago

13 contributors +1

753 lines (753 sloc) | 71.4 KB   Raw Blame

```
Tag                Who      Date  Summary
============================================================================================================
    ctsm5.1.dev098 swensosc 05/20/2022 Correct perched water table calculation
    ctsm5.1.dev097    sacks 05/20/2022 Update ccs_config to fix issue on izumi and maybe elsewhere
    ctsm5.1.dev096     erik 05/18/2022 Fix a few glitches from the last tag
    ctsm5.1.dev095     erik 05/09/2022 Turn soil BGC off for FATES-SP mode, externals updates, FatesSP user-mod directory and compset
    ctsm5.1.dev094   negins 05/06/2022 subset_data allows zeroing out nonveg landunits without any dompft selected
    ctsm5.1.dev093   slevis 05/03/2022 Modifications for FATES-MIMICS to work
    ctsm5.1.dev092    sacks 04/29/2022 Refactor NutrientCompetition / CNAllocation to provide hooks for AgSys
    ctsm5.1.dev091   rgknox 04/22/2022 clm decomp method is now passed to fates to enabled mimics coupling
    ctsm5.1.dev090 samrabin 03/31/2022 Fix misleading name of "gddplant"
    ctsm5.1.dev089    sacks 03/31/2022 For CLM45 apply peaklai to aleaf in grainfill
    ctsm5.1.dev088 samrabin 03/28/2022 Add outputs for annual crop sowing and harvest dates
    ctsm5.1.dev087    sacks 03/24/2022 Reduce aux_clm testing cost
    ctsm5.1.dev086   negins 03/22/2022 Updates necessary for NEON v2 files and server updates
    ctsm5.1.dev085    sacks 03/16/2022 Expand crop reproductive pools; remove some unused options
    ctsm5.1.dev084 glemieux 03/15/2022 FATES parameter file updated to align with clm pft optical parameters
    ctsm5.1.dev083 multiple 03/08/2022 Implement PCT_URBAN_MAX to minimize dynamic urban memory
    ctsm5.1.dev082   slevis 02/28/2022 Replace dom_nat_pft with dom_plant to enable crop in fsurdat_modifier tool
    ctsm5.1.dev081 swensosc 02/24/2022 Do not subtract irrigation from QRUNOFF diagnostic
    ctsm5.1.dev080    sacks 02/24/2022 Use avg days per year when converting param units
    ctsm5.1.dev079    sacks 02/24/2022 Changes to CropPhenology timing
    ctsm5.1.dev078    sacks 02/24/2022 Rework single-point testing
    ctsm5.1.dev077   rgknox 02/22/2022 Updates to FATES API, including removal of patch dimensions from fates history and using soil instead of ground layers for fates history
    ctsm5.1.dev076   negins 02/18/2022 updating subset_data.py script and move to the Python package.
    ctsm5.1.dev075     erik 02/16/2022 Small answer changes: urban ventilation, fire-emission, irrigate off when not crop, fix two SSP ndep files
    ctsm5.1.dev074   slevis 02/02/2022 Introduce vert. resolved MIMICS as new method to solve below ground decomp.
    ctsm5.1.dev073    sacks 01/25/2022 Some fixes for Gregorian calendar
    ctsm5.1.dev072   negins 01/17/2022 mksurfdat toolchain part 1: gen_mksurf_namelist
    ctsm5.1.dev071 glemieux 01/16/2022 Small changes to enable new fates dimension and update fates tag
    ctsm5.1.dev070 multiple 01/10/2022 Update externals, remove need for LND_DOMAIN_FILE and LND_DOMAIN_PATH, etc.
    ctsm5.1.dev069 multiple 12/15/2021 Implement dynamic (transient) urban capability
    ctsm5.1.dev068 multiple 12/13/2021 Adding fsurdat_modifier tool
    ctsm5.1.dev067 jedwards 12/13/2021 NEON UI update, externals updates, small miscellanouse fixes
```

Atmospheric Fluxes

- **Dynamic Urban**, new urban datasets, & building property parameterization [Keith Oleson]
- Surface roughness modifications [Ronnie Myer]
- Dust emissions and more [Longlei Li, Natalie Mahowald, Danny Lueng, Jasper Kok]
- **Updated PFT optical properties** [Keith Oleson]
- **Biomass heat storage** [Sean Swenson]
- **Snow burial of vegetation** [Danica Lombardozzi]
- Multilayer canopy [Gordon Bonan & Ned Patton]

Hydrology

- Representative hillslope hydrology [Sean Swenson & others]
- Water isotopes [Bill Sacks]
- Excess Ice [Lei Cai, Matvey Debolskiy]
- **Irrigation [Bill Sacks & Sean Swenson]**
- mizuRoute [Naoki Mizukami & Erik Kluzek]
- Reservoir operations and dynamic lakes [Inne Vanderkelen]

Ecosystems and Biogeochemistry

- **FATESsp**, no competition, and other simplified configurations. [Rosie Fisher, Charlie Koven, Jackie Shuman, Adrianna Foster & many more]
- FATES point and regional configurations [Jackie, Adrianna, Polly, others]
- **MIMICS-CN soil bgc model** [Will W. & Sam Levis]
- **Ozone impacts on Jmax** in LUNA [Stefanie Falk]
- **Fire Model: bug fixes, improvements, & tuning [Fang Li]**
- **Arctic/Boreal phenology & allocation [Leah Birch]**
- CN-Matrix for biogeochemistry [Chris Lu & Yiqi Luo]
- Aerosols: FAN (NH3 emissions) [Julius Vira & Peter Hess]
- Terrestrial DOM fluxes and transport in river model [Dev N.]

Crop Model

- **Clean up crop phenology**, planting & harvest dates [Sam Rabin]
- **Bioenergy crop** [Yanyan Cheng & Maoyi Huang]
- **Winter wheat** [Yaqiong Lu], **implemented but not currently used**
- Shifting cultivation [Peter Lawrence]
- APSIM crop phenology [Bin Peng]
- Tillage and crop residue management [Mike Graham & Danica L]
- Soil degradation with Land Use [Johann Feddema, Pei-Ling]

Features

- **Switch to NUOPC** [Erik, Mariana]
- Single point & regional workflow including **NEON simulations**, supported towers & generic grid cells [Danica L, Negin Sobhani, Will Wieder, Adrianna Foster, Erik]
- Parameter Perturbation Ensemble [Daniel, Katie, Dave]
- **Moving hard coded parameters to parameter file** [Keith Oleson]
- Simple Land Model, SLIM [Marysa Lague]
- Tool chain modifications part 1 [Sam, Bill, Negin]
- **WRF-CTSM beta release** [Dave Lawrence & more]
- **No anthro compsets**: turn off irrigation, crop, urban, LULCC, fire
- **Prescribed soil moisture** [Sean Swenson]
- **Soil and snow layer flexibility + trimming land units & PFTs** [Sam Levis & Bill Sacks]
- **SSP-RCP anomaly forcing compsets** for land only simulations

- **Bold items** have been merged into CTSM5.1_main
- Linked items point to github pull requests.
- Highlighted items are outstanding CTSM5.1 milestones
- Highlighted items will require new datasets that will come in for CTSM5.2.

2. Improving the BEM in CESM

New explicit-AC-adoption scheme

Table 1. *Comparison of the original and new AC adoption modeling scheme.*

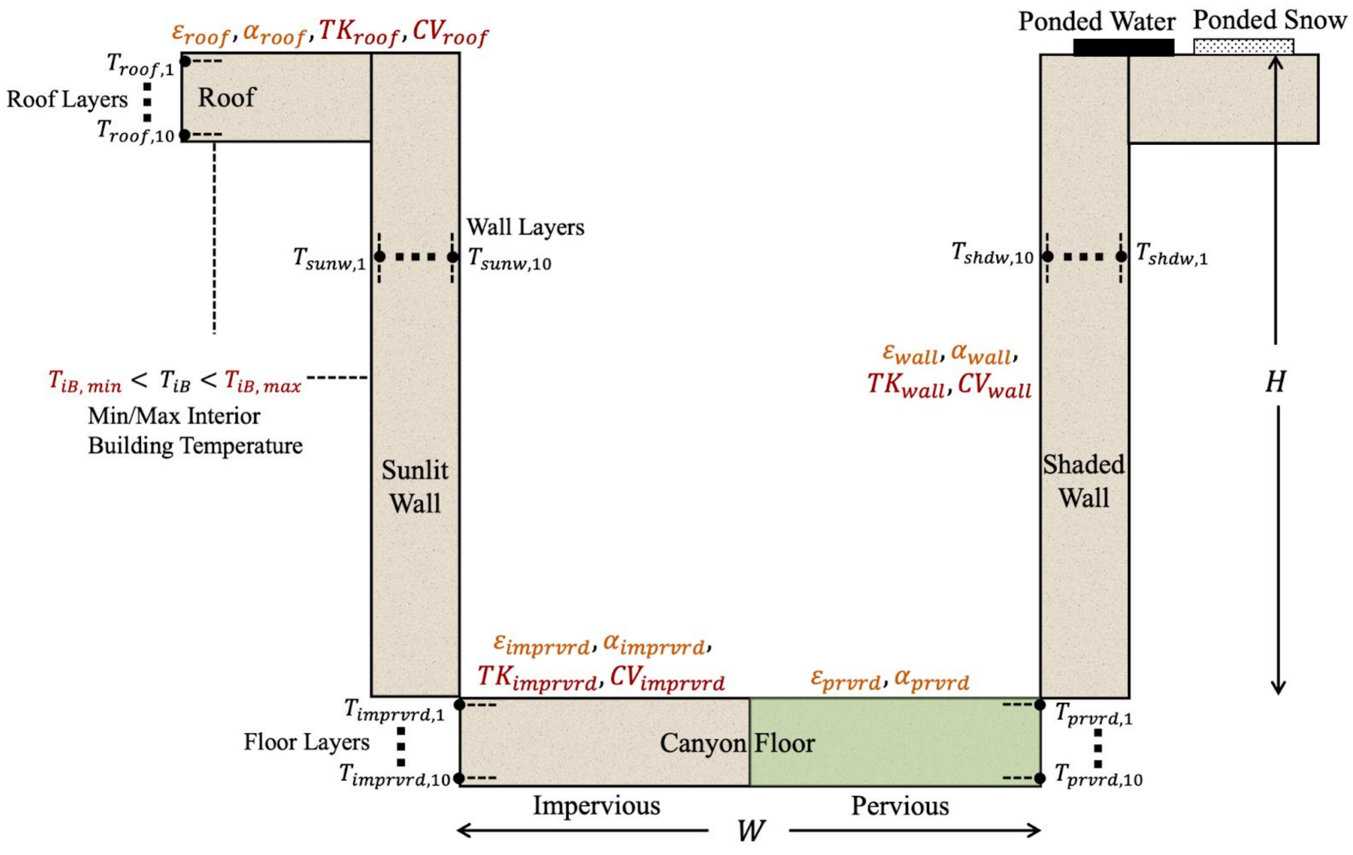
	Original	**New**
AC adoption	Implicitly modeled by proxy setpoint T_{max}	Explicit AC adoption rate, $\boldsymbol{p_{AC}}$ + Saturation setpoint at 100% adoption, $\boldsymbol{T_{sat,max}}$
AC trigger	Indoor temperature $T_{i_B}^{t+1} > T_{max}$	$T_{i_B}^{t+1} > \boldsymbol{T_{sat,max}}$
AC flux	$F_{AC} = \frac{H\rho C_p}{\Delta t}\left(T_{i_B}^{t+1} - T_{max}\right)$	$F_{AC} = \boldsymbol{p_{AC}} \cdot F_{sat,AC}$, where $F_{sat,AC} = \frac{H\rho C_p}{\Delta t}\left(T_{i_B}^{t+1} - \boldsymbol{T_{sat,max}}\right)$
Updating $T_{i_B}^{t+1}$	$T_{i_B}^{t+1} = T_{max}$	$T_{i_B}^{t+1} = \frac{(1-\boldsymbol{p_{AC}})F_{sat,AC} \cdot \Delta t}{H\rho C_p} + \boldsymbol{T_{sat,max}}$

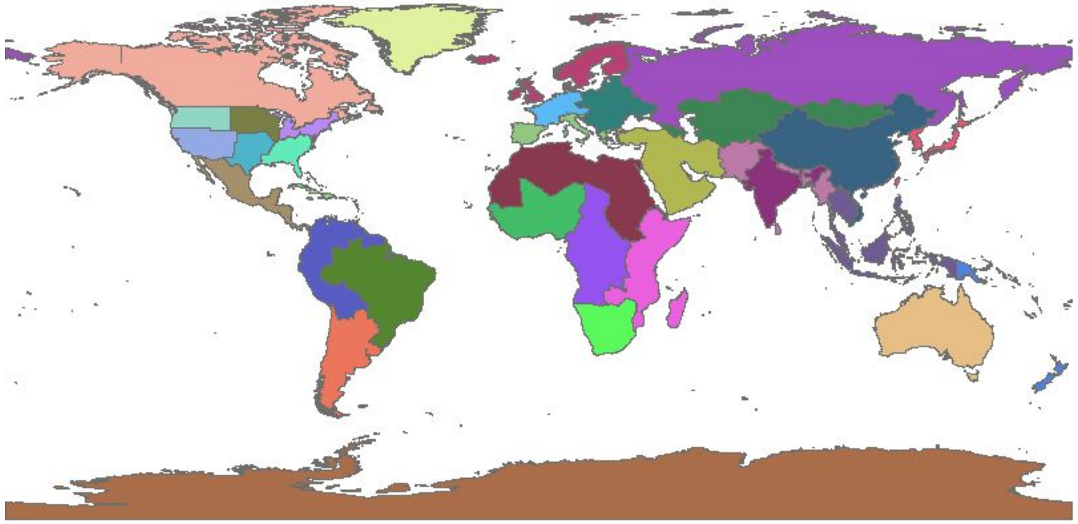
H: building height [m], ρ: air density [kg/m^3], C_p: specific heat of dry air [J/kg-K], Δt: timestep of simulation [s]; t+1 denotes the next time step.

Li et al. *in press* (2024)

3. Global high-res urban representation for km-level Earth system modeling

Urban surface parameters

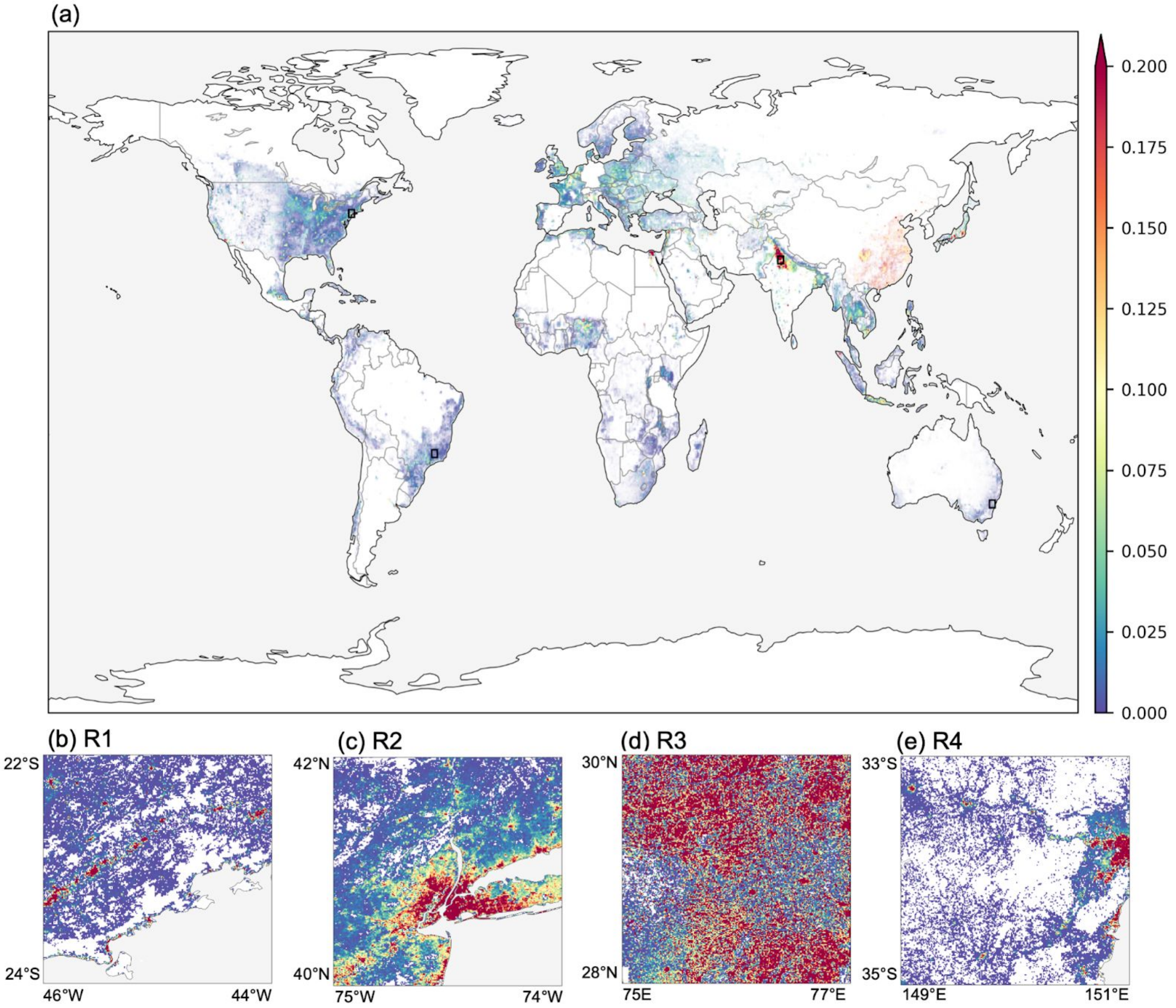




Cheng et al. to be submitted (2024)

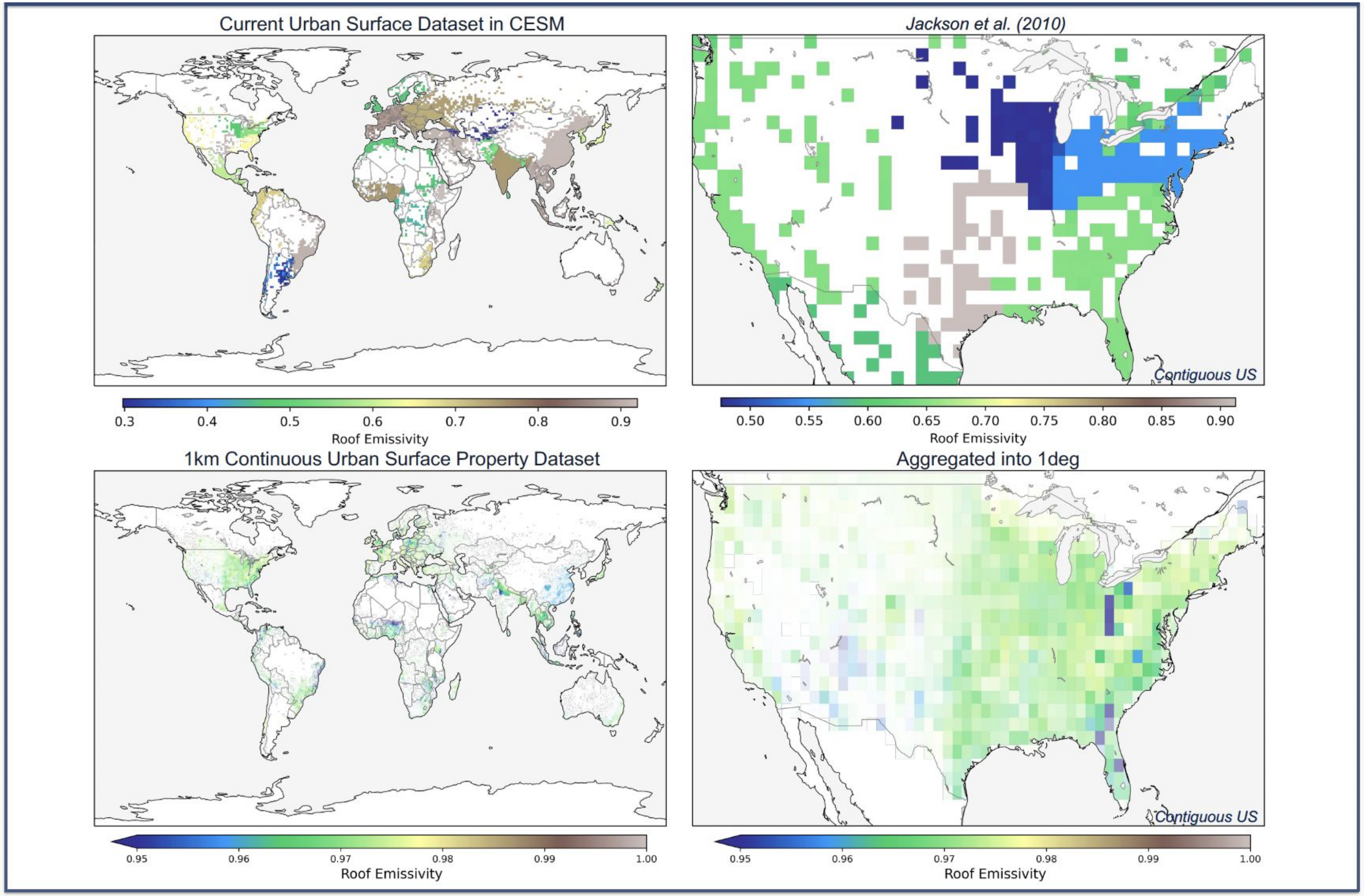
Category	Urban Parameters	This Study
Radiative	Roof Emissivity	• Source: 100m ASTER v3 satellite emissivity product • Time span: 2000-2008 • Resolution: 1km
	Impervious Road Emissivity	
	Pervious Road Emissivity	
	Wall Emissivity	
	Roof Albedo	• Source: 10m Sentinel2 satellite albedo product and NTB algorithm • Time span: 2019-2021, 2021-2022 • Resolution: 1km
	Impervious Road Albedo	
	Pervious Road Albedo	
	Wall Albedo	
Morphological	Roof Height	• Source: • Time span: • Resolution: 1km
	Canyon Height-to-width Ratio	• Source: infinite canyon street model (Masson et al., 2020) • Time span: • Resolution: 1km
	Roof Fraction	• Source: Microsoft global building footprints • Time span: 2014-2021 • Resolution: 1km
	Pervious Road Fraction	• Source: 10m ESA Worldcover v200 • Time span: 2021-2022 • Resolution: 1km
	Urban Percentage	• Source: 1km global urban extent (Gao and O'Neill, 2020) • Time span: 2000 • Resolution: 1km
Thermal	Air Conditioning Penetration Rate	• Source: global AC penetration rate (Li et al., 2024) • Time span: • Resolution: national-level
	Number of Impervious Road Layers	• Source: local building codes, municipal documentation • Time span: • Resolution: Regional-level, density-class-specific
	Roof Thickness	
	Wall Thickness	
	Minimum Interior Building Temperature	
	Maximum Interior Building Temperature	
	Roof Thermal Conductivity	
	Impervious Road Thermal Conductivity	
	Wall Thermal Conductivity	
	Roof Volumetric Heat Capacity	
	Impervious Road Volumetric Heat Capacity	
	Wall Volumetric Heat Capacity	

Cheng et al. to be submitted (2024)

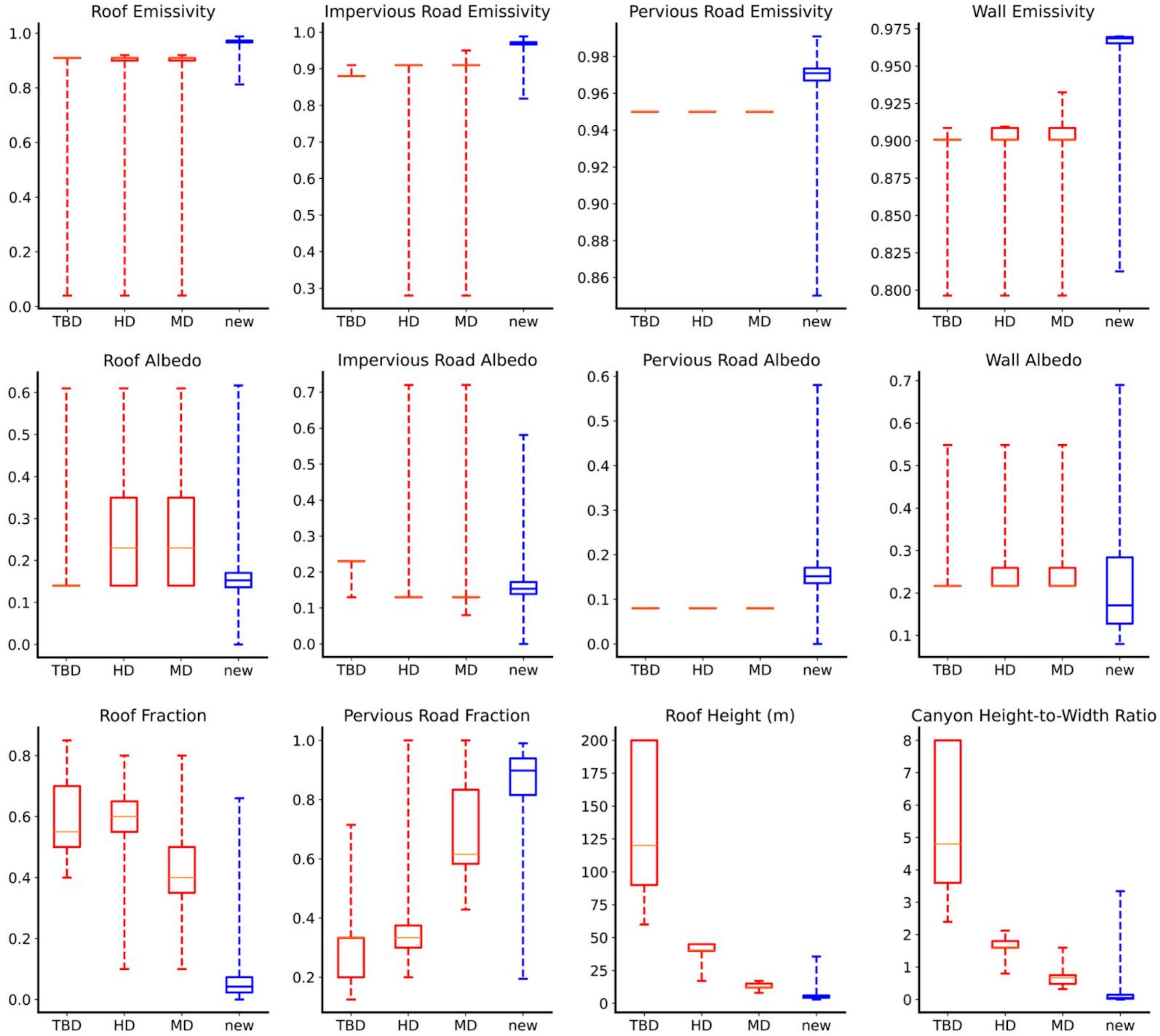


Spatial distribution of roof fraction

Cheng et al. to be submitted (2024)



Cheng et al. to be submitted (2024)

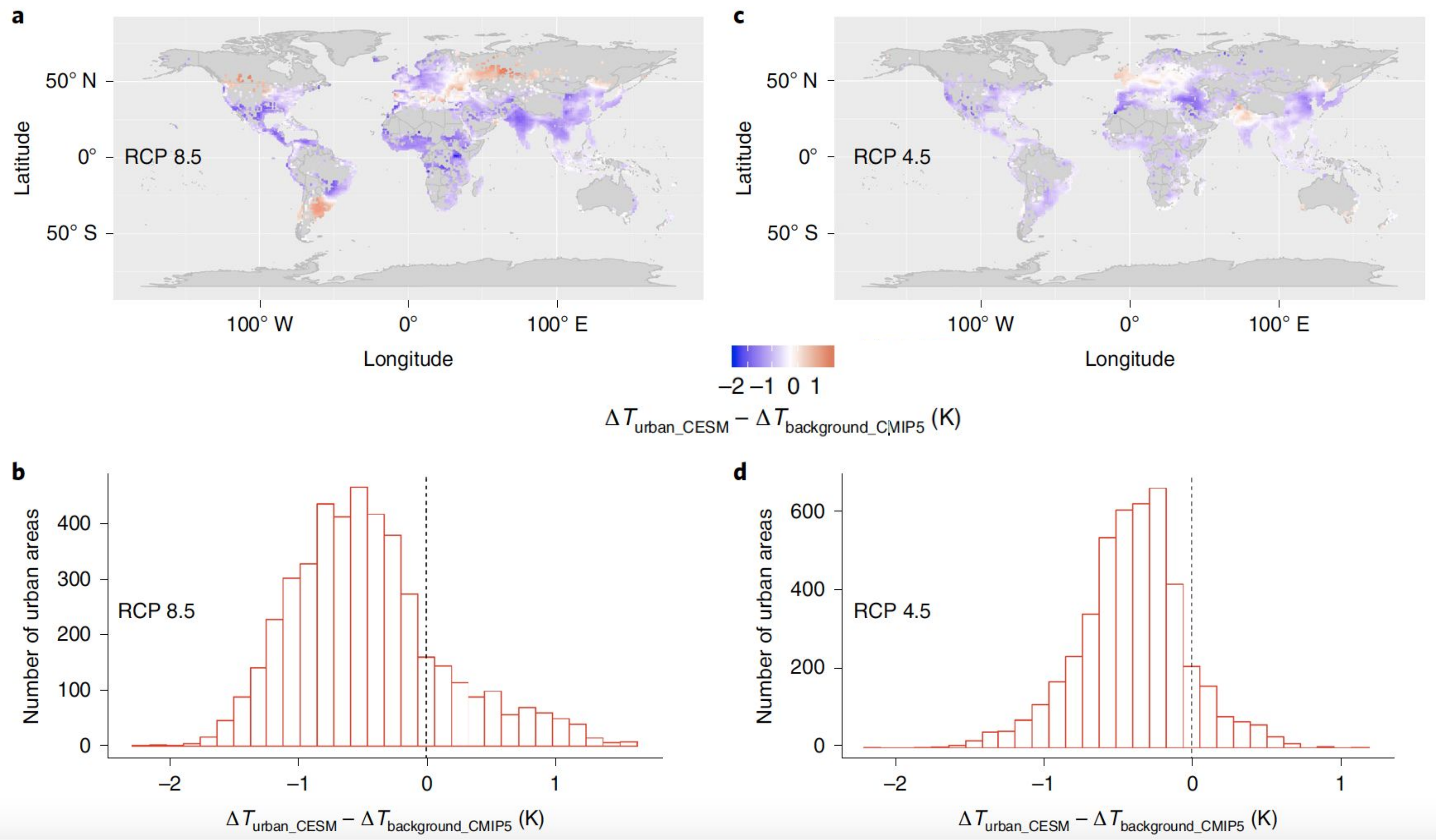


Cheng et al. to be submitted (2024)

Thank you!

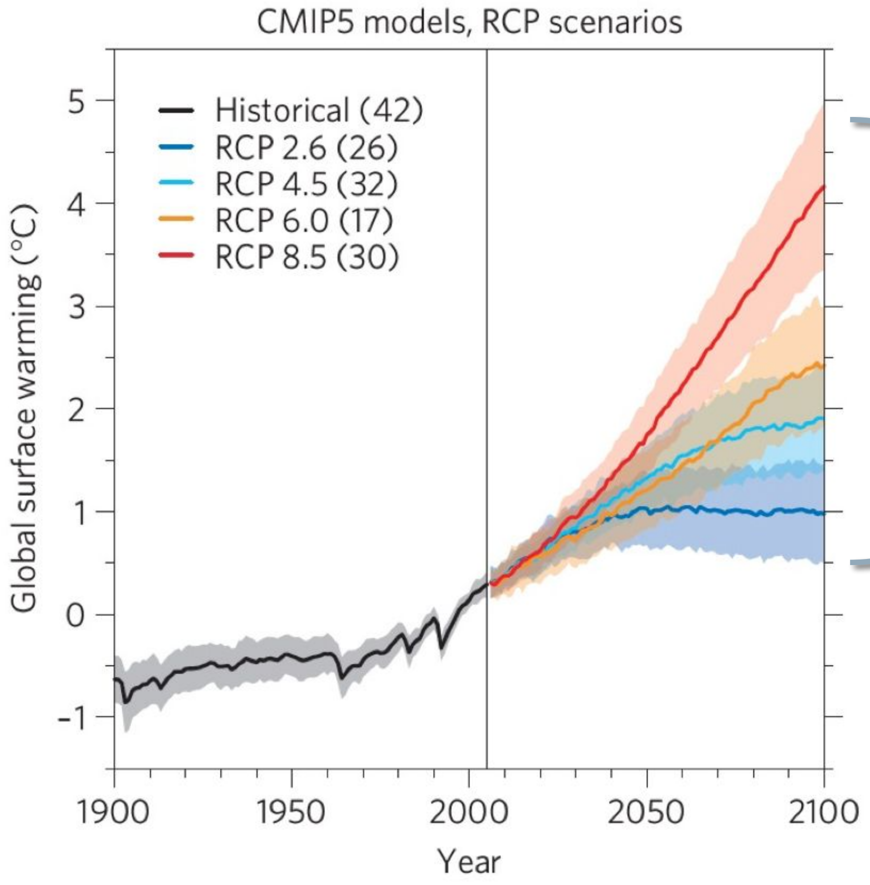
Comments & questions?

Traditional CMIP multi-model projections fail to capture urban warming signals



Zhao et al. *Nature Climate Change* (2021)

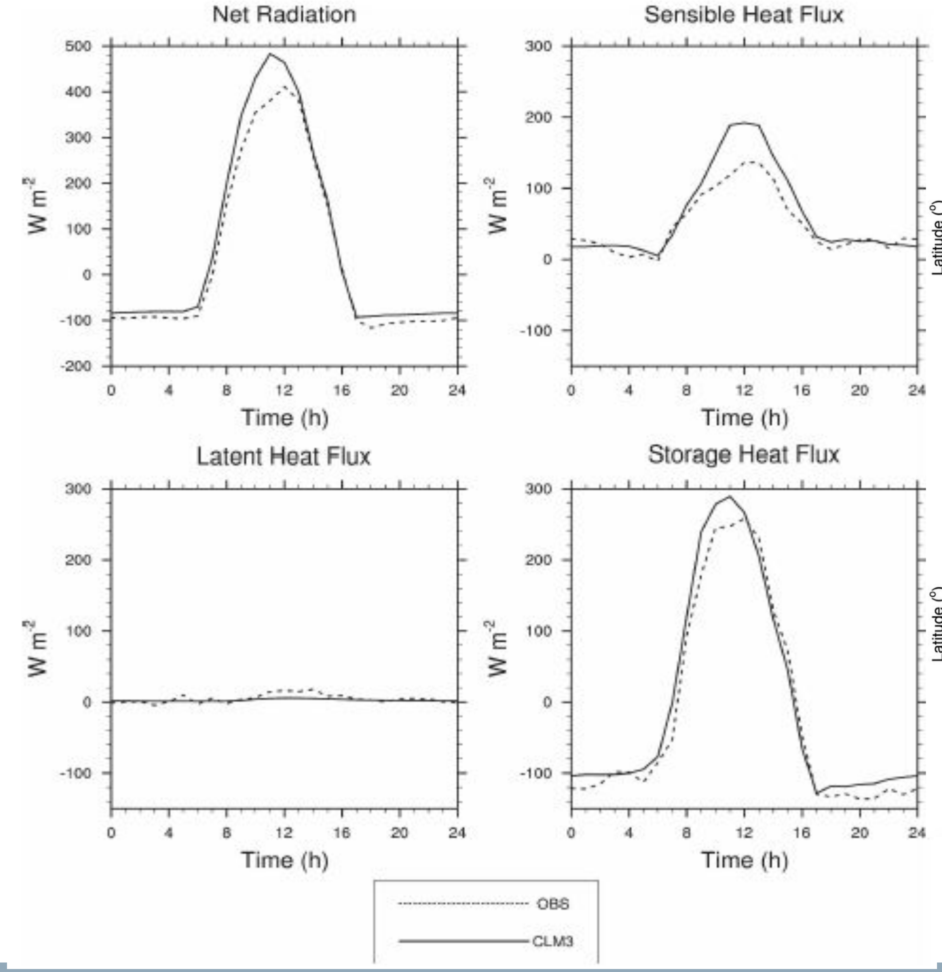
Understanding the uncertainties

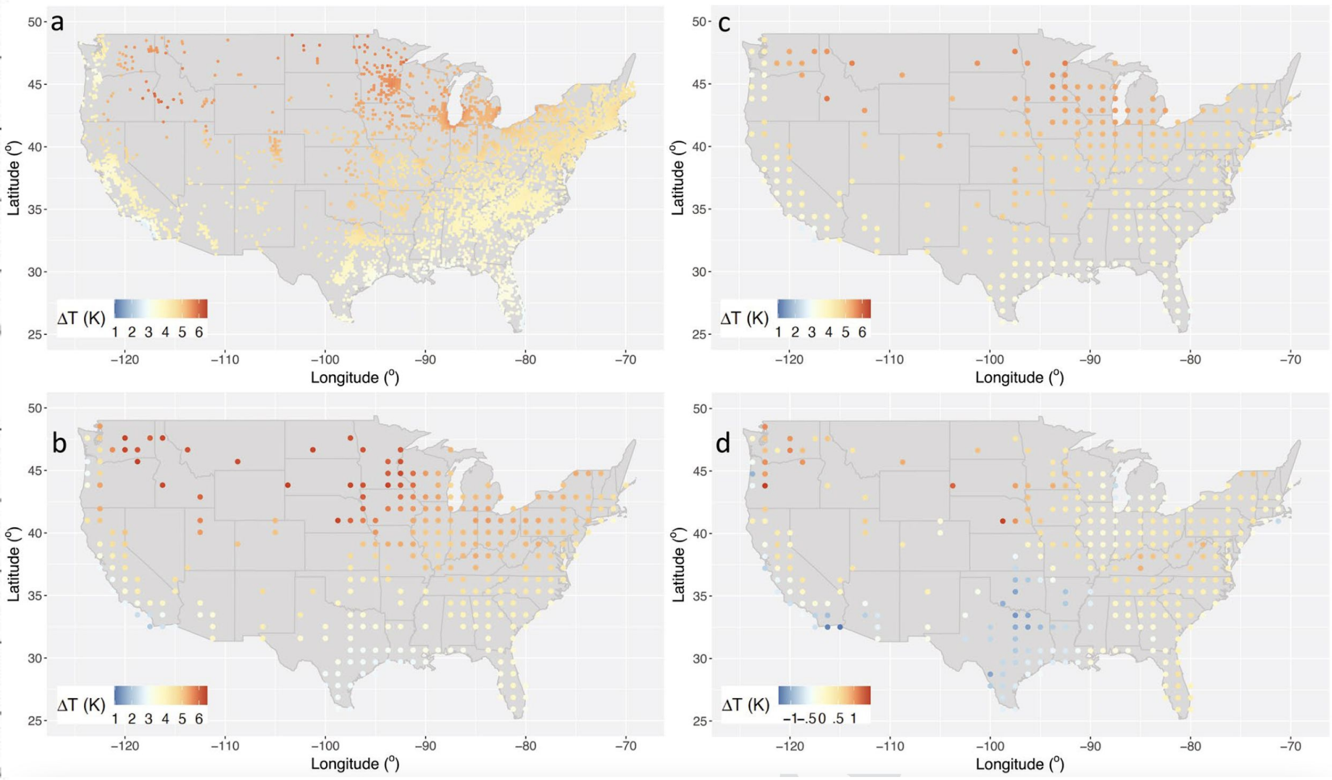


Internal variability
+
Structural uncertainty
+
Parameter uncertainty
+
Scenario uncertainty

Dominant source of uncertainty at the time horizons of multiple decades or longer

Evaluation of the CESM urban modeling

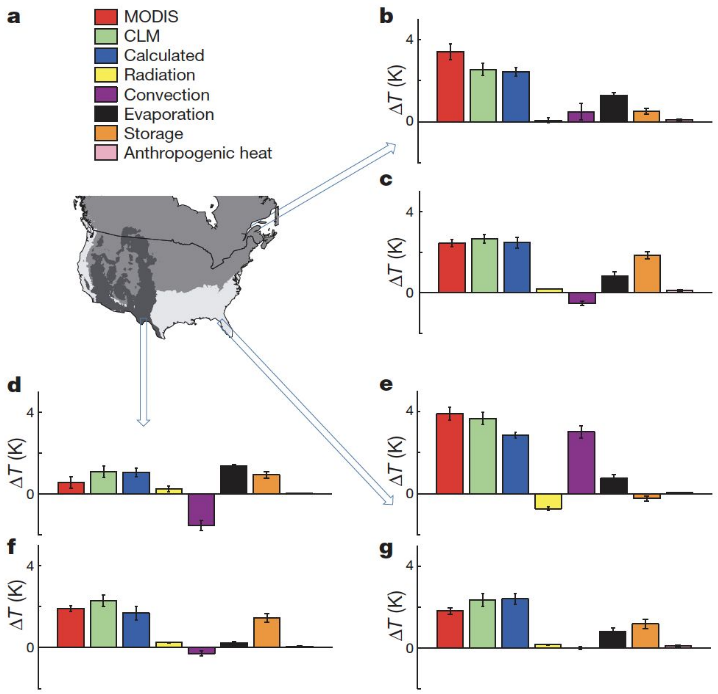




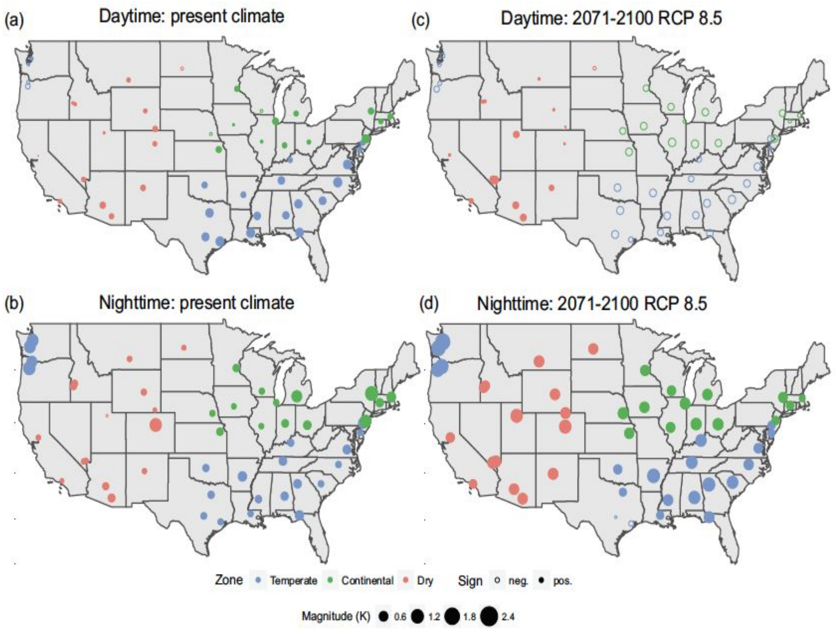
Source: Oleson et al. 2008

Source: Zhao et al. *Nature Climate Change* (2021)

Urban warmth

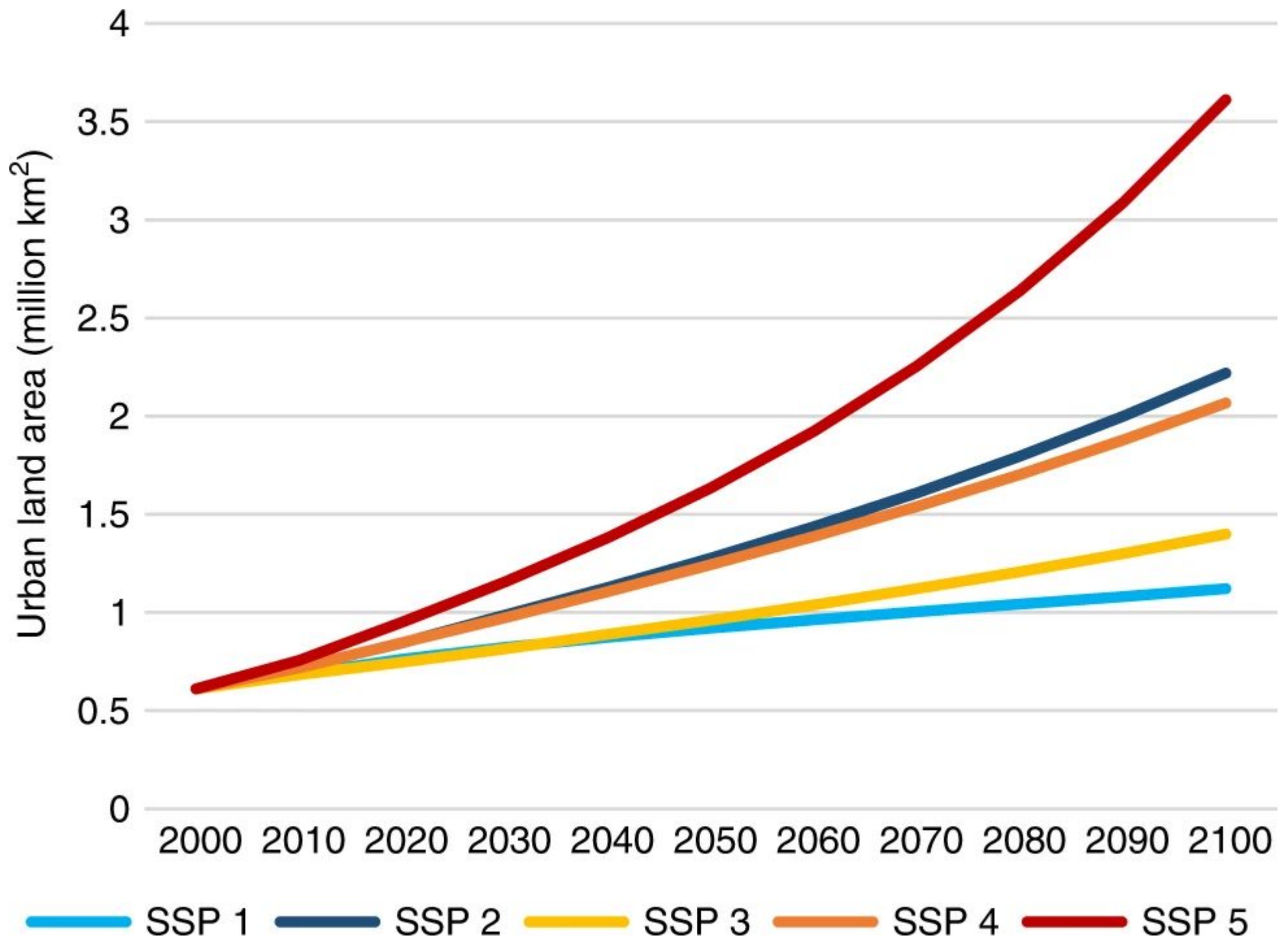


Ref: Zhao et al. *Nature* 2014



Ref: Zhao et al. *Env. Res. Lett* 2018

Urban growth



Gao, Jing, and Brian C. O'Neill, 2020

Source: Gao and O'Neil *Nature Communications* 2020