Enhancing Urban Climate-Energy Modeling in CESM through Explicit Representation of Urban Air-conditioning Adoption

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CESM Land Model & Biogeochemistry Winter Working Group Meeting

February 26, 2024
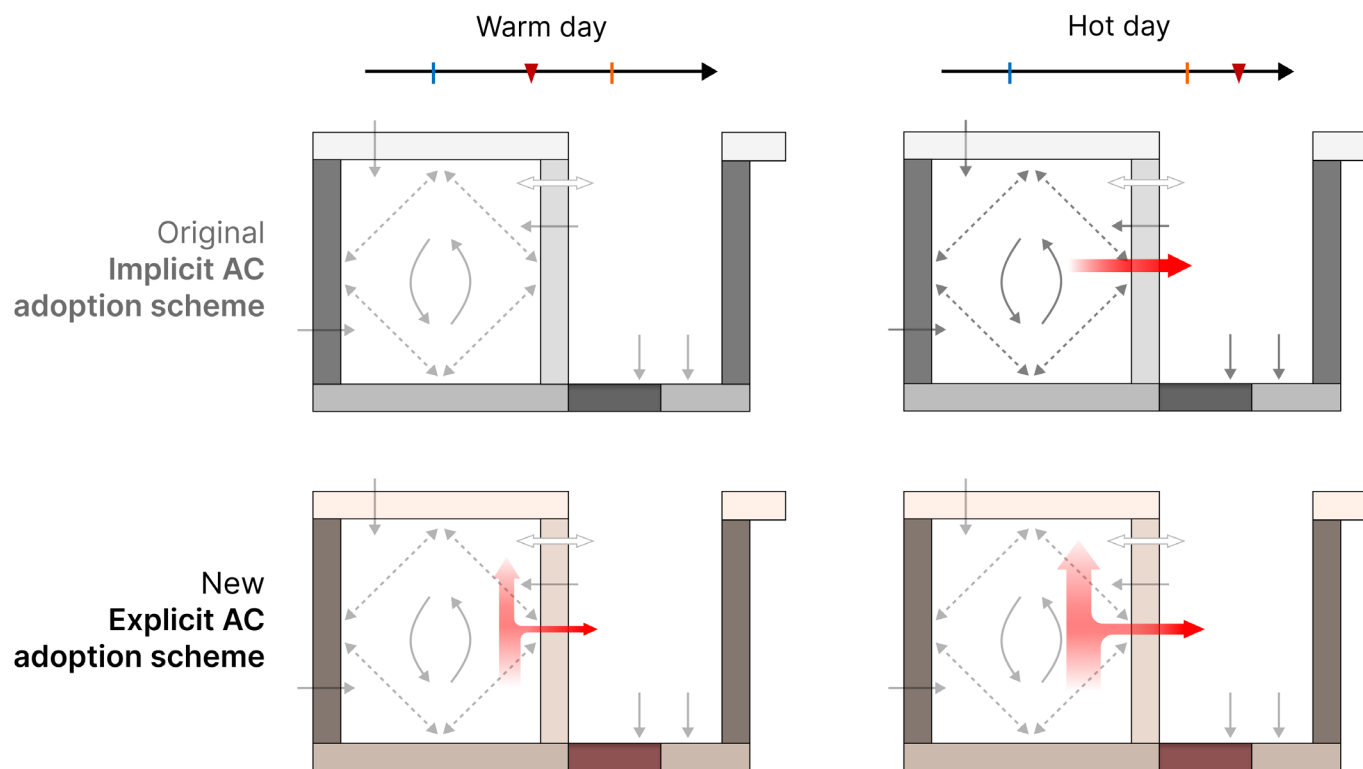
There is a growing interest in connecting energy and climate modeling to address climate change and energy security.
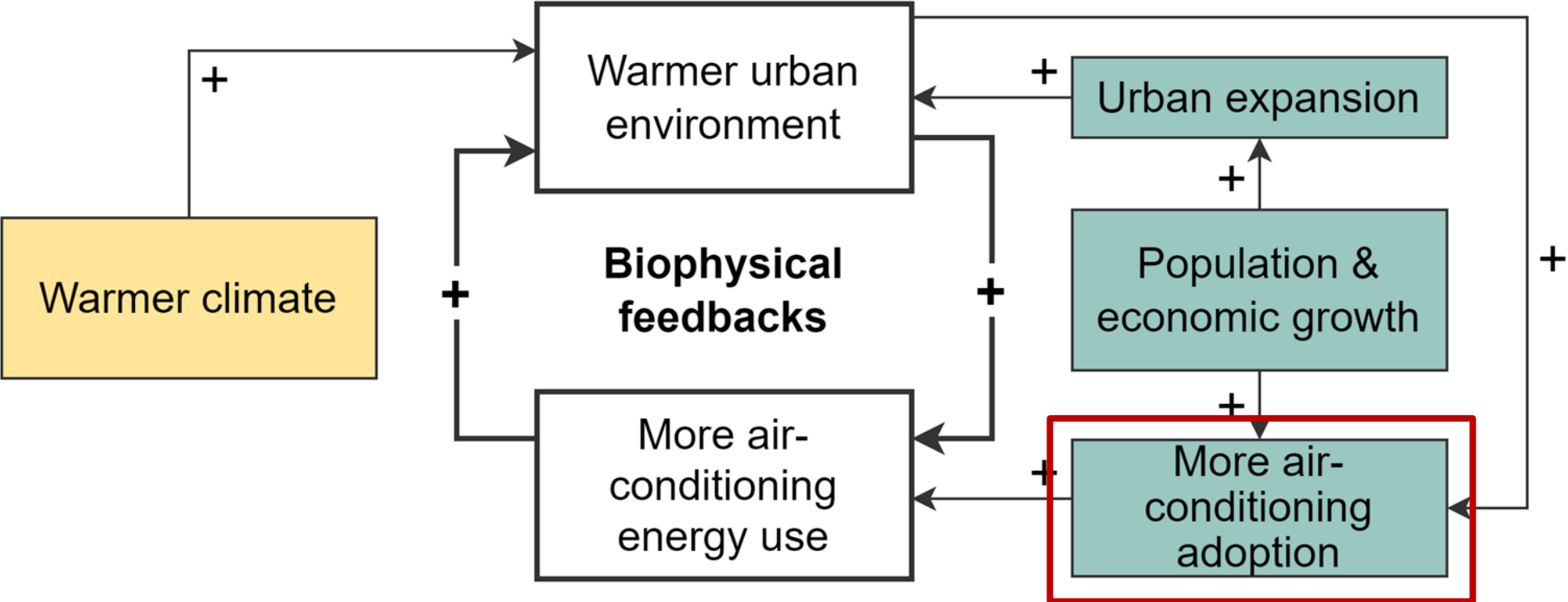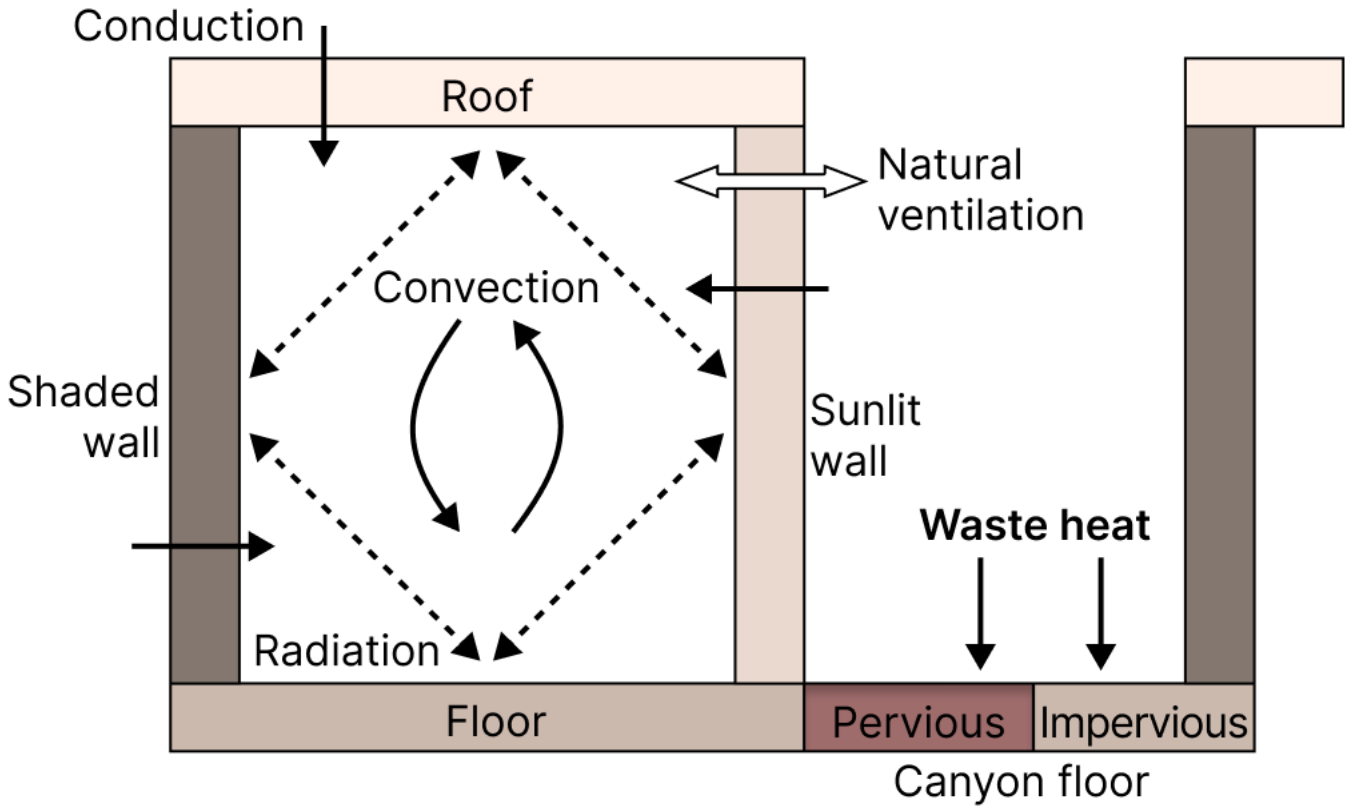
The Community Terrestrial System Model (CTSM) has an urban module, but lacks infrastructure to model air-conditioning (AC) adoption explicitly.
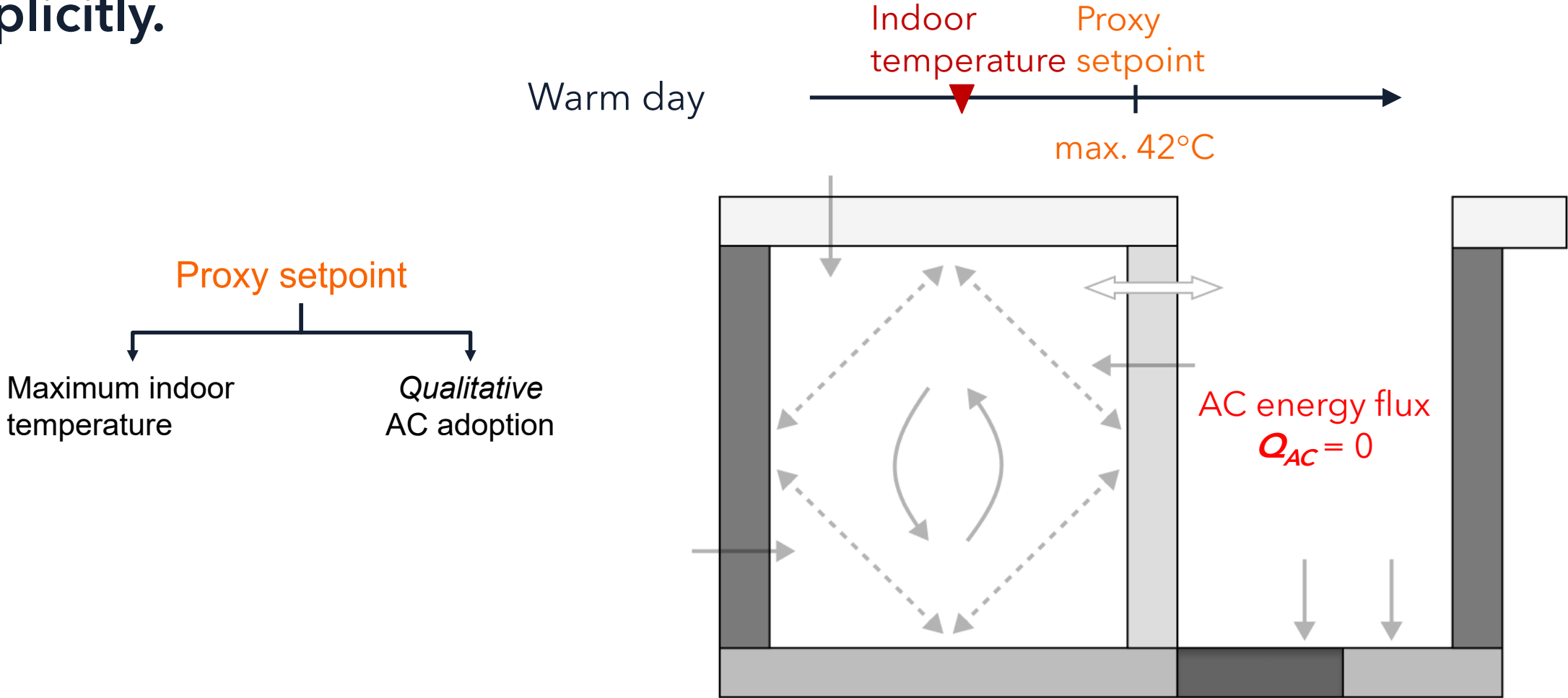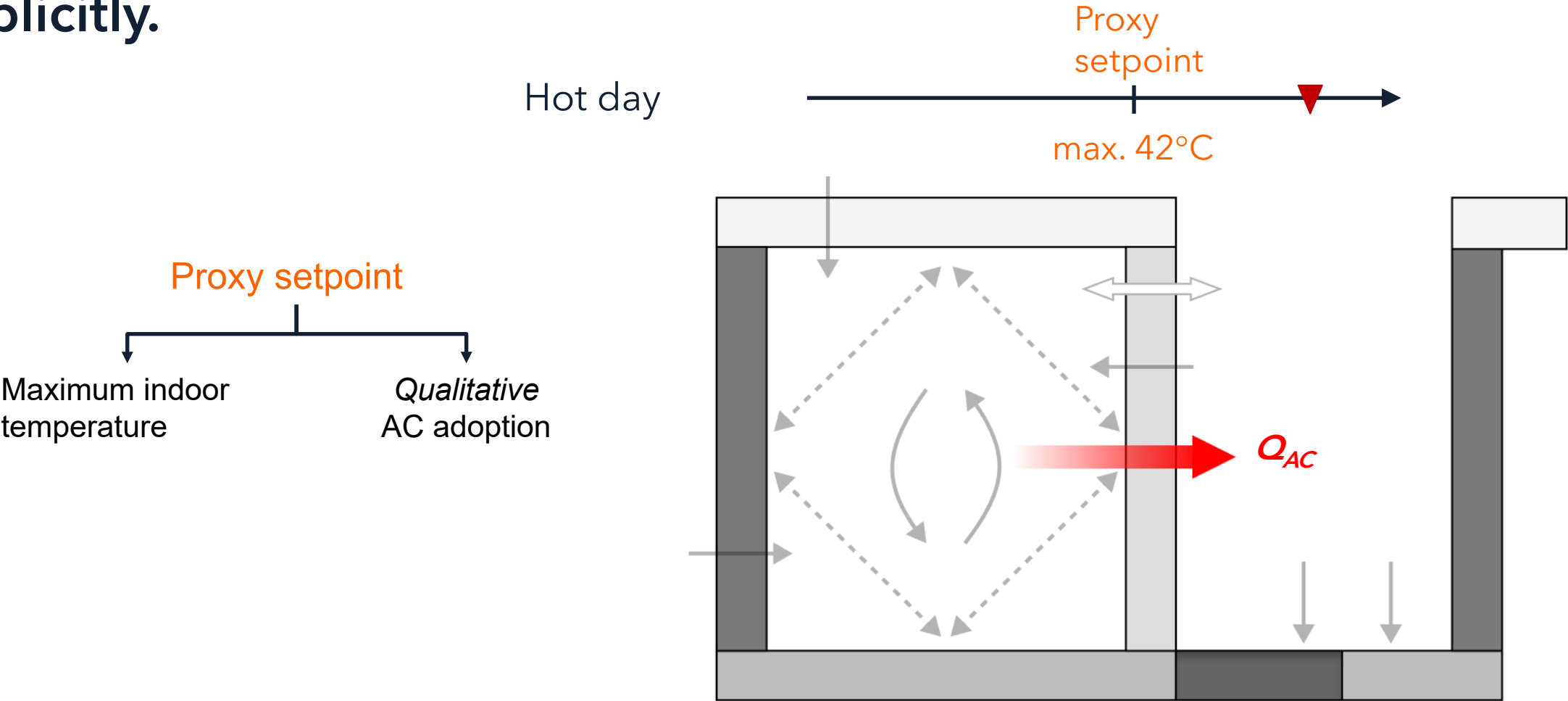
CTSM

Urban

Conduction

Roof

Natural ventilation

Convection

Shaded wall

Sunlit wall

Waste heat

Radiation

Floor

Pervious

Impervious

Canyon floor

The Community Terrestrial System Model (CTSM) has an urban module, but lacks infrastructure to model air-conditioning (AC) adoption explicitly.
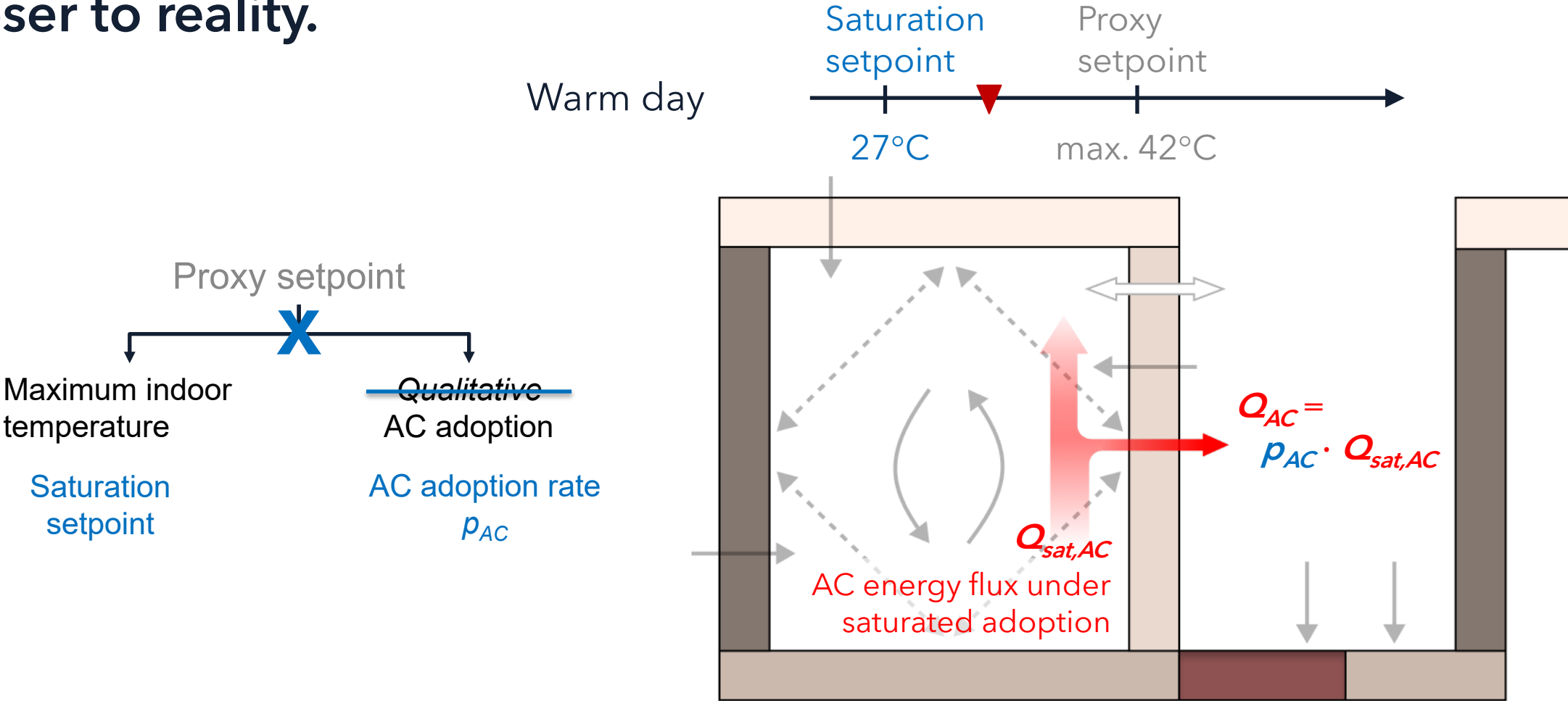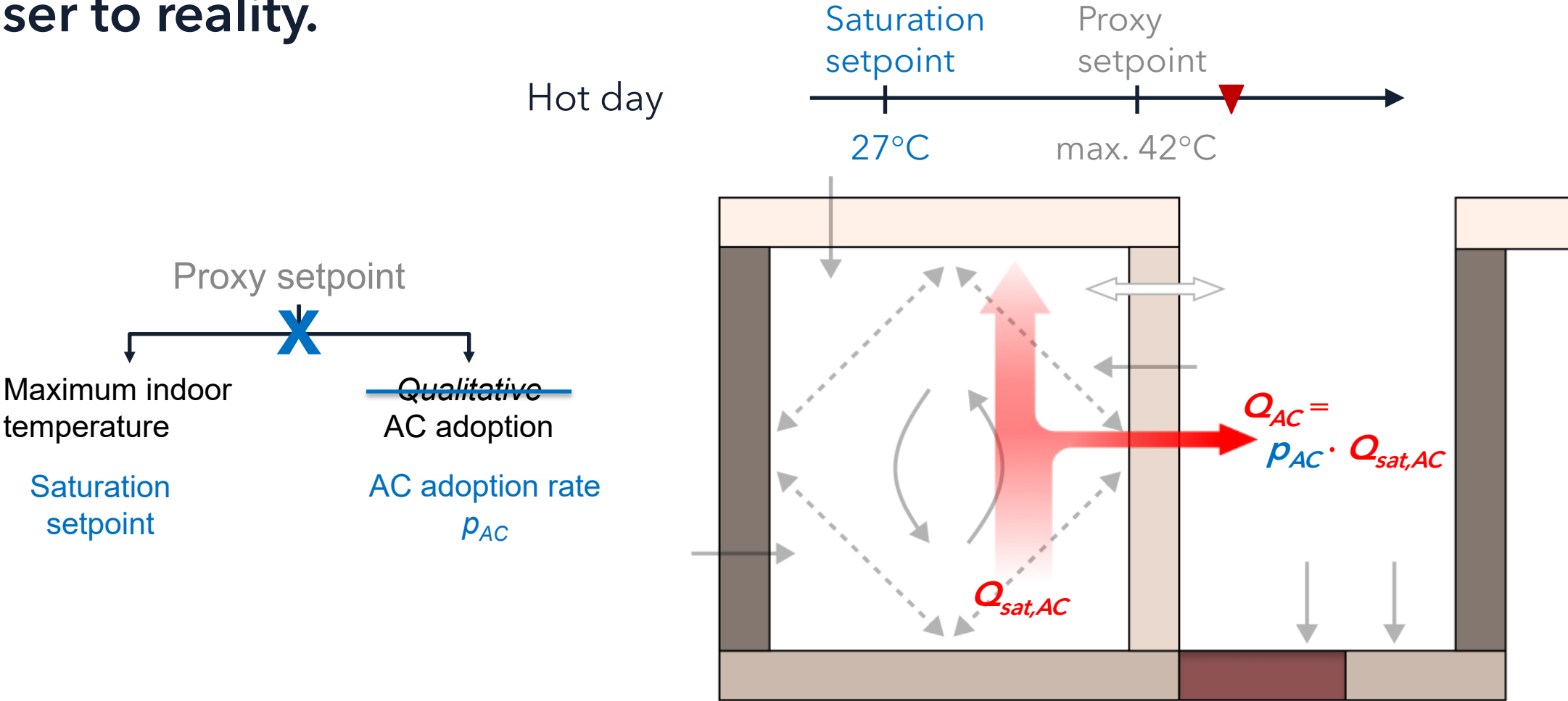

Warm day

Indoor temperature

Proxy setpoint

max. 42°C

Proxy setpoint

Maximum indoor temperature

Qualitative AC adoption

AC energy flux
$Q_{AC} = 0$

The Community Terrestrial System Model (CTSM) has an urban module, but lacks infrastructure to model air-conditioning (AC) adoption explicitly.

Hot day

Proxy setpoint

max. 42°C

Proxy setpoint

Maximum indoor temperature

Qualitative AC adoption

Q_{AC}

The Community Terrestrial System Model (CTSM) has an urban module, but lacks infrastructure to model air-conditioning (AC) adoption explicitly.

Hot day

Proxy setpoint

max. 42°C

- ✘ Physical interpretability
- ✘ Daily/hourly results
- ✘ Model accuracy
- ✘ Projections under future AC adoption rate
- ✘ Inter-model and inter-region comparison
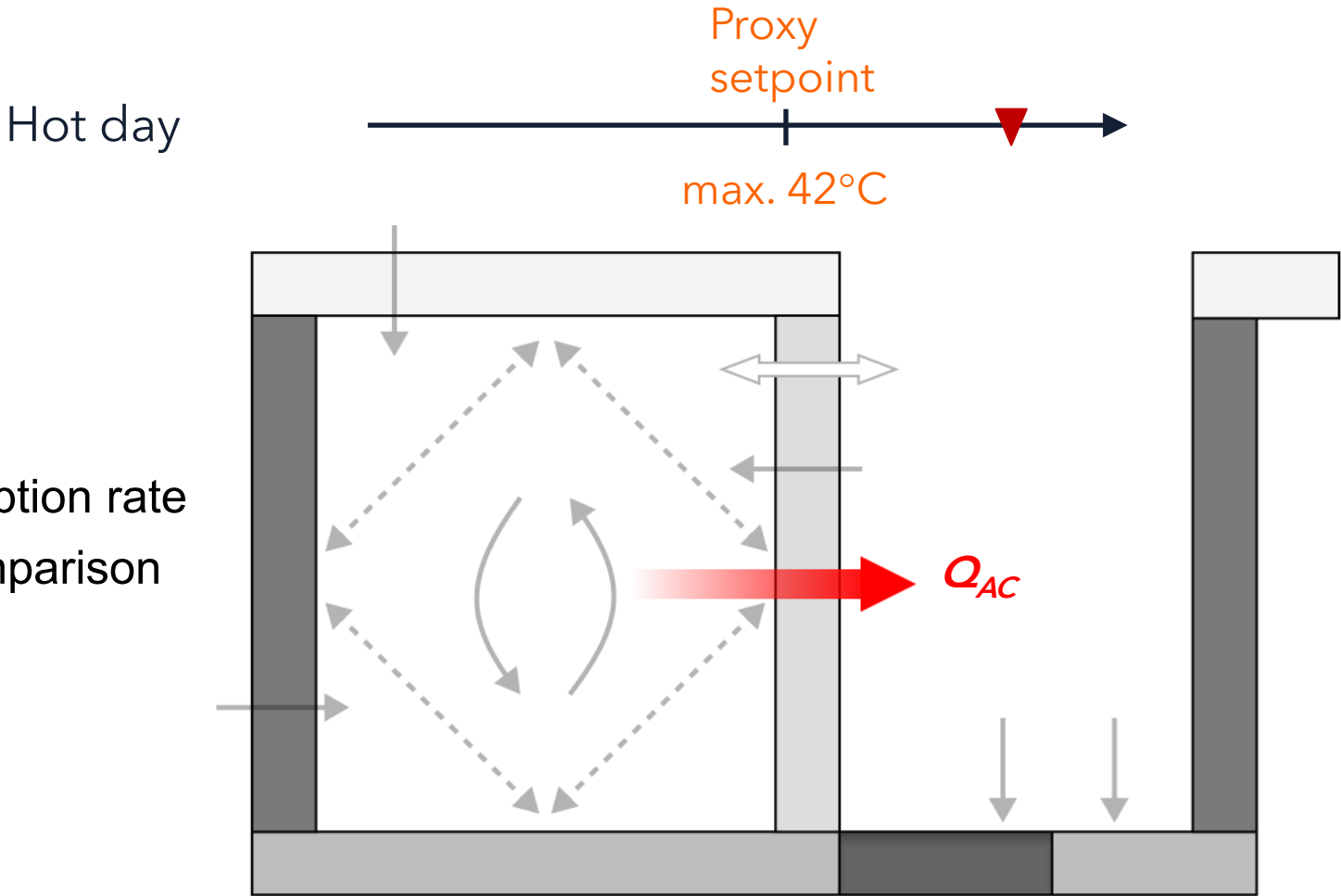
Q_{AC}

We develop an explicit-AC-adoption scheme by introducing an explicit AC adoption rate parameter (p_{AC}), and bringing setpoints closer to reality.

Warm day

Saturation setpoint

Proxy setpoint

27°C   max. 42°C

Proxy setpoint

✗

Maximum indoor temperature

~~Qualitative~~ AC adoption

Saturation setpoint

AC adoption rate p_{AC}

$Q_{AC} = p_{AC} \cdot Q_{sat,AC}$

$Q_{sat,AC}$

AC energy flux under saturated adoption

We develop an explicit-AC-adoption scheme by introducing an explicit AC adoption rate parameter (p_{AC}), and bringing setpoints closer to reality.

Hot day

Saturation setpoint — 27°C

Proxy setpoint — max. 42°C

Proxy setpoint

X

Maximum indoor temperature

~~Qualitative~~ AC adoption

Saturation setpoint

AC adoption rate p_{AC}

$Q_{AC} = p_{AC} \cdot Q_{sat,AC}$

$Q_{sat,AC}$

The explicit-AC-adoption scheme will be integrated into CTSM.

Pull request:

We build a present-day, global, survey-based, and spatially explicit AC adoption rate dataset at country and sub-country level.

AC adoption rate data

- **35 countries/regions** from International Energy Agency (IEA), literature, national surveys, etc.

- **U.S. states** from U.S. Energy Information Agency

- **Australia states** from Australia Bureau of Statistics

- **China provinces** from China National Bureau of Statistics

AC adoption rate, %

0   20   40   60   80   100
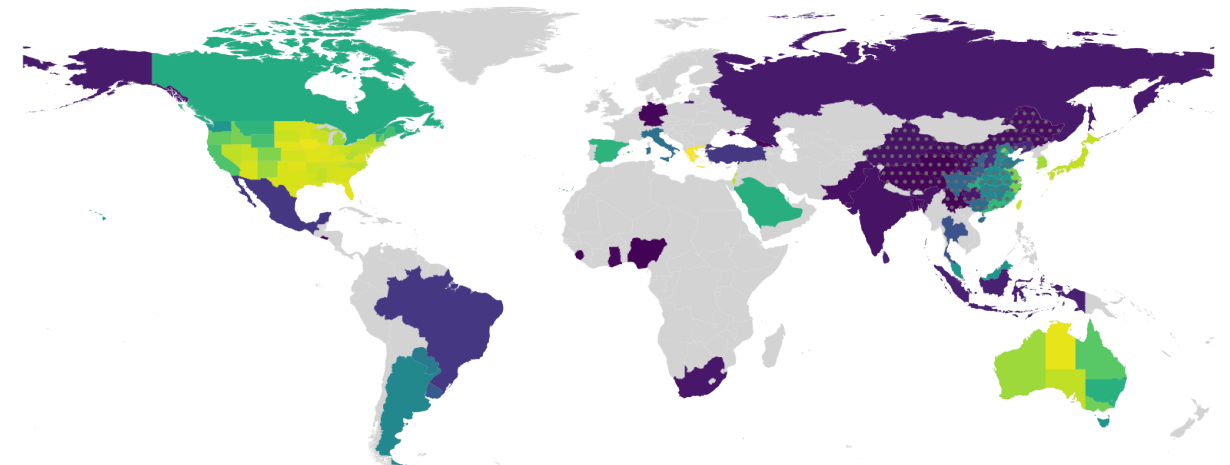
Derived from number of AC units per household

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AC adoption rate data

- **35 countries/regions** from International Energy Agency (IEA), literature, national surveys, etc.

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Number of AC units per household data

- **196 countries/regions** from IEA

- **China provinces** from China National Bureau of Statistics
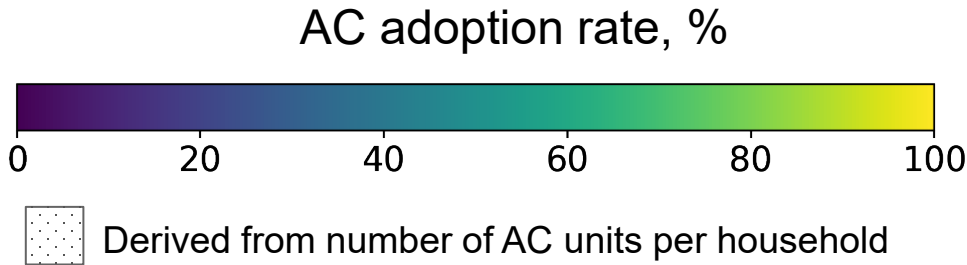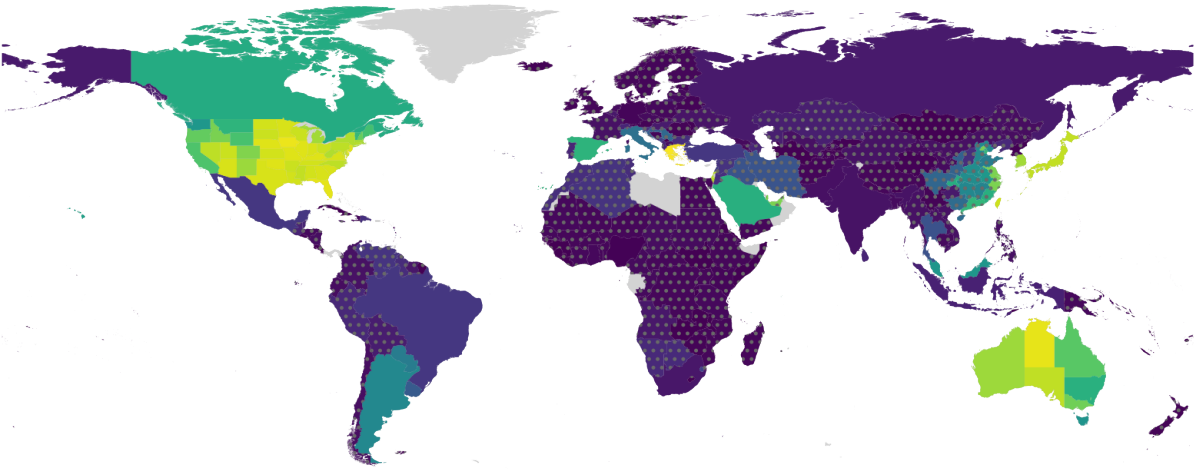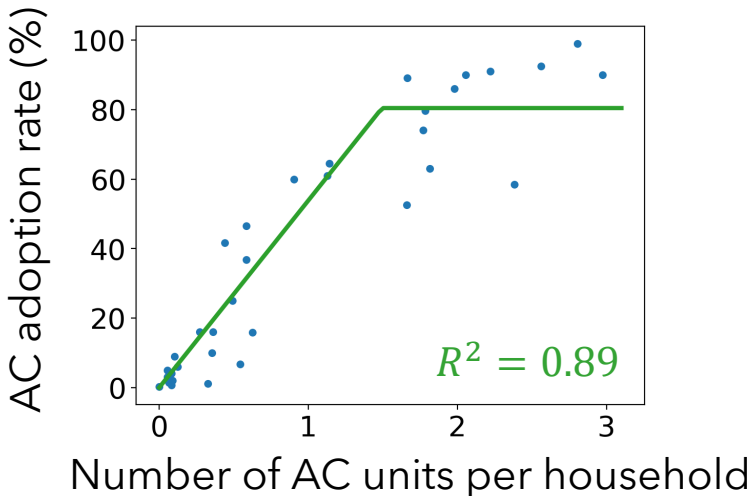
$R^2 = 0.89$

AC adoption rate (%) vs Number of AC units per household

AC adoption rate, %

0   20   40   60   80   100

Derived from number of AC units per household

We grid the dataset to the desired resolution, then perform grid-cell-based nearest neighbor gap filling.

AC adoption rate

We grid the dataset to the desired resolution, then perform grid-cell-based nearest neighbor gap filling.

AC adoption rate
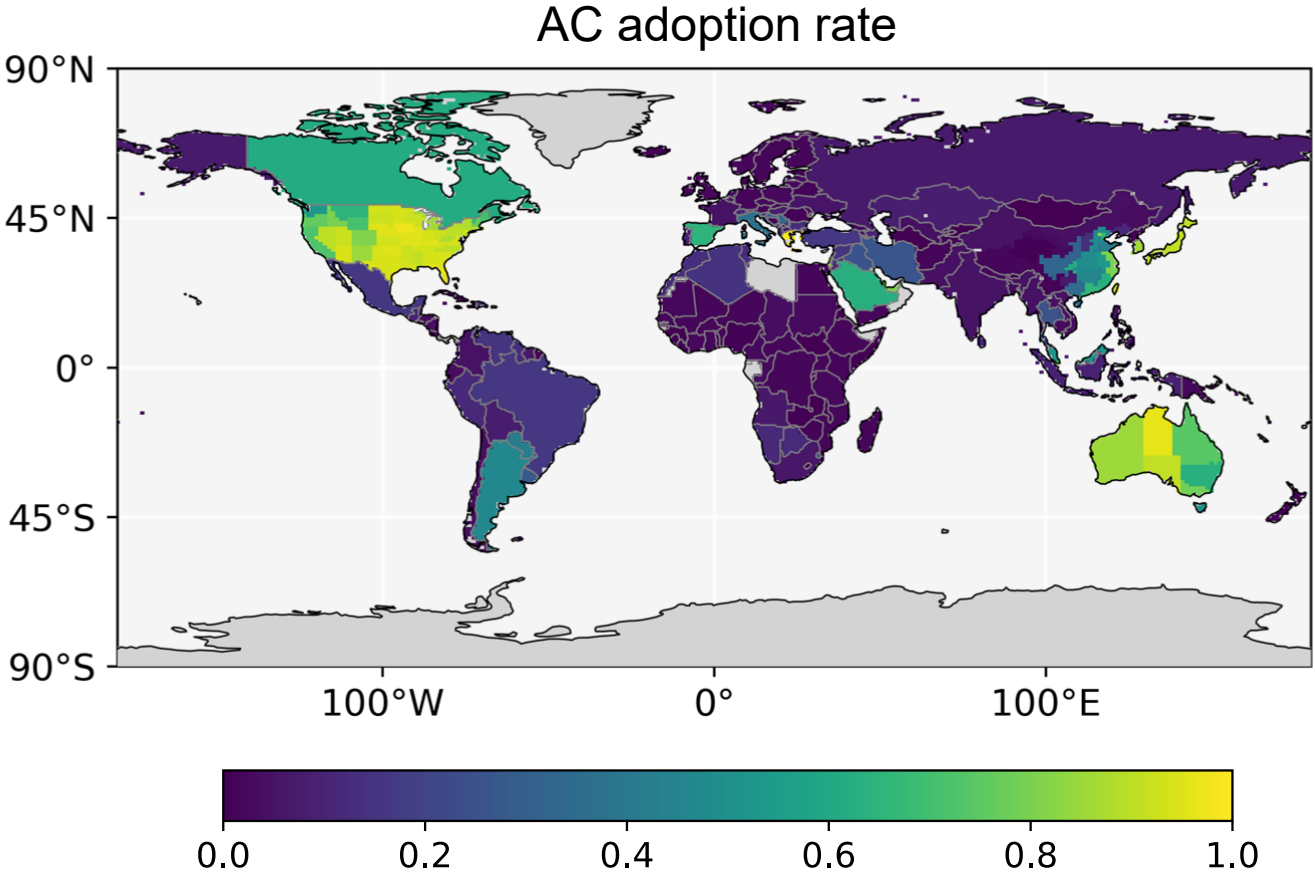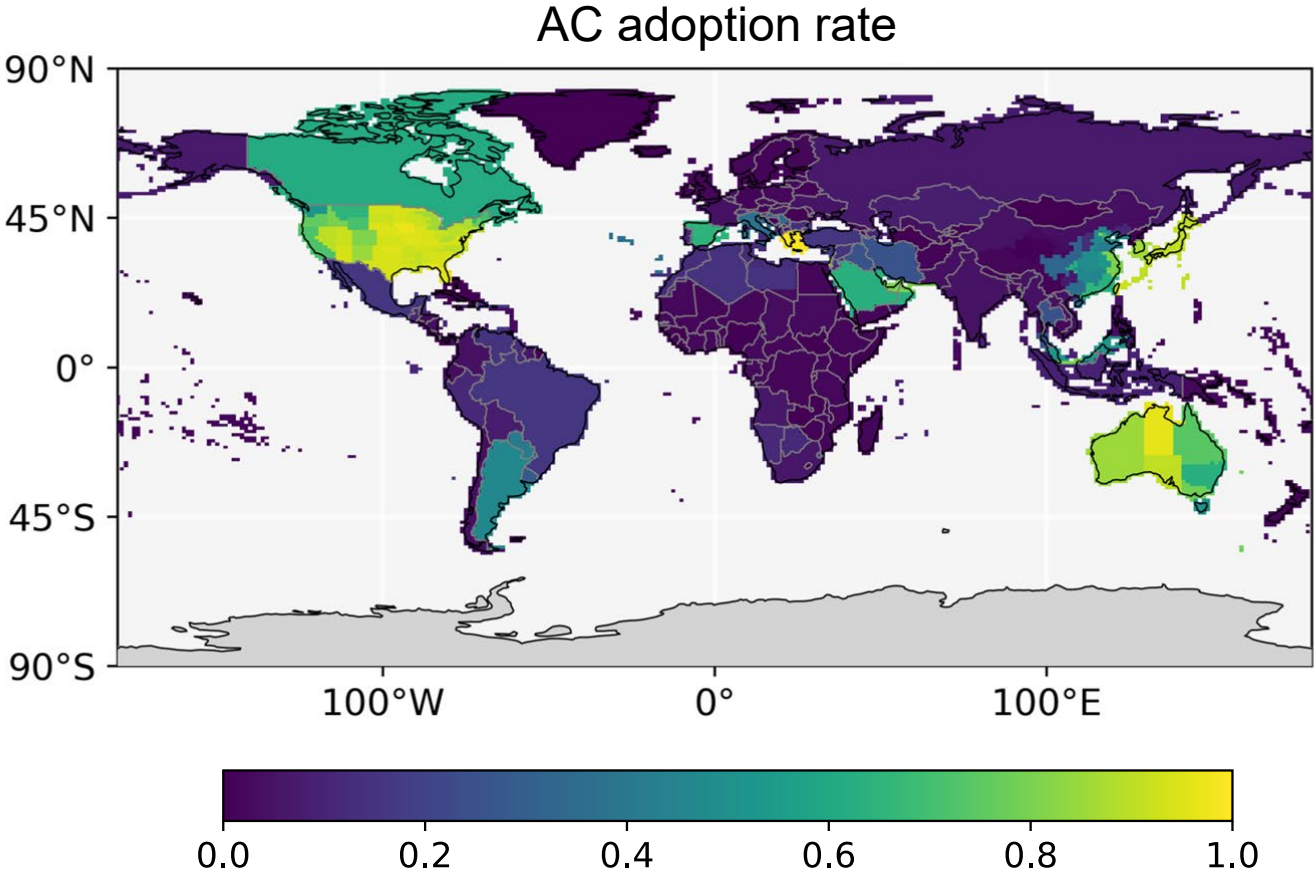
The dataset is publicly available in tabular, gridded, and geospatial formats for use in ESMs and other models/analyses.

zenodo

Search records...

Communities   My dashboard

Dataset:

Published February 8, 2024 | Version v1

Dataset   🔓 Open
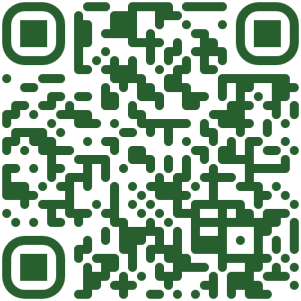
Global present-day air-conditioning adoption rate

Li, Xinchang[1] (iD); Zhao, Lei[1] (iD); Oleson, Keith W.[2]; Zhou, Yuyu[3]; Qin, Yue[4]; Zhang, Keer[5];
Fang, Bowen[1]

📁 global_AC_adoption_rate

    📄 global_AC_adoption_rate_README.txt

    📄 p_ac_283countries-regions_qc.csv

    📁 p_ac_gridded

    📁 p_ac_shapefile

The new scheme and dataset improve AC energy flux simulation in both magnitude and spatial correlation.

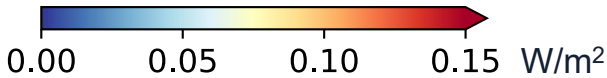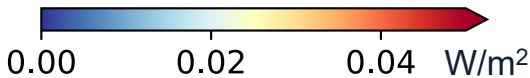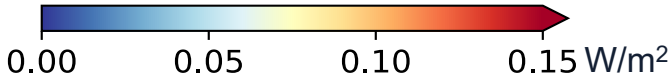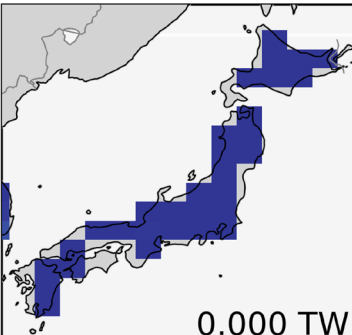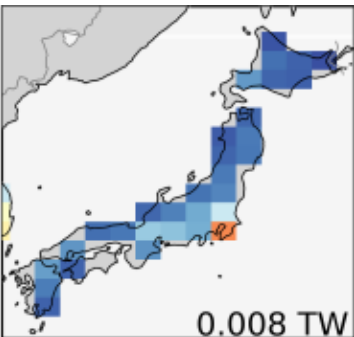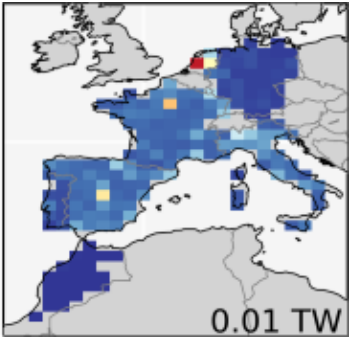**Anthropogenic heat flux due to AC:**

Observational estimates

Total anthropogenic heat

0.12 TW
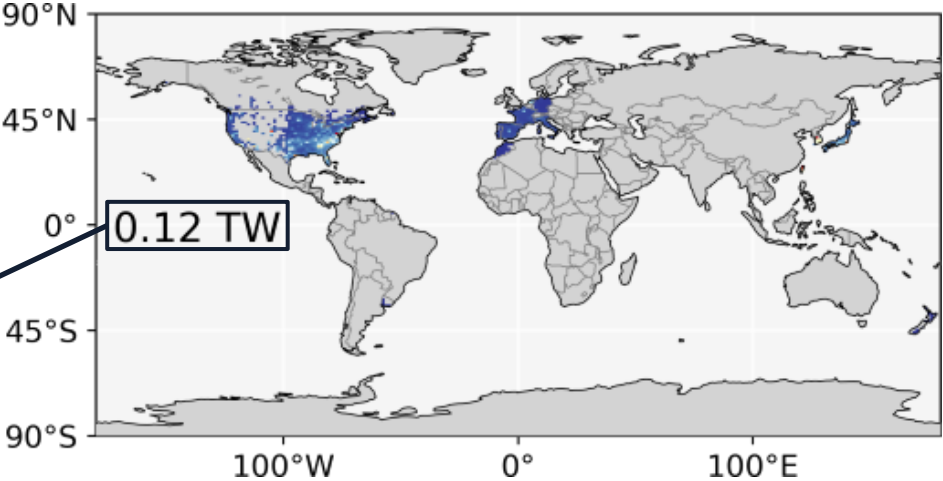
R = 0.38

Original Implicit AC adoption

0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14   W/m²

The new scheme and dataset improve AC energy flux simulation in both magnitude and spatial correlation.

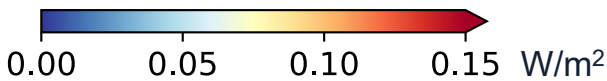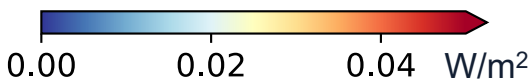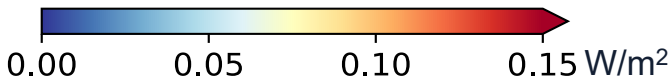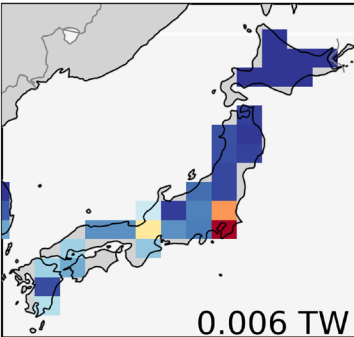**Anthropogenic heat flux due to AC:**

Observational estimates

Total anthropogenic heat

0.12 TW

R = 0.58

**New
Explicit AC adoption
scheme + dataset**
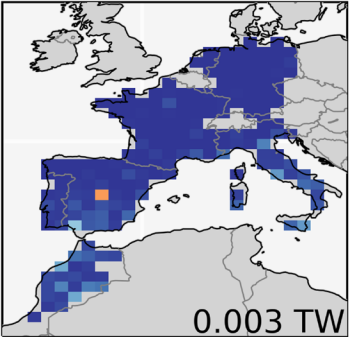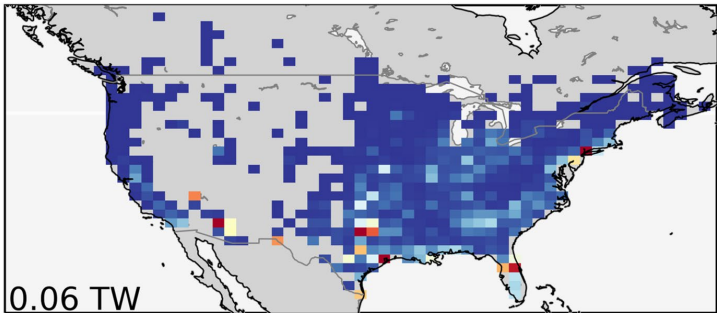
0.08 TW

0.00   0.02   0.04   0.06   0.08   0.10   0.12   0.14   W/m²

The new scheme and dataset improve AC energy flux simulation in both magnitude and spatial correlation.

Anthropogenic heat flux due to AC:

Figs. 5 & 6, Li et al. *JAMES* (in press)

The new scheme and dataset improve AC energy flux simulation in both magnitude and spatial correlation.

Anthropogenic heat flux due to AC:

Figs. 5 & 6, Li et al. *JAMES* (in press)

The explicit AC adoption scheme enables global-scale experiments on the effects of changing AC adoption using CTSM.

Changes in …

AC adoption rate (p_{AC})   **AC energy flux**   **urban 2m air temperature**

Between simulations of:

p_{AC} = 1
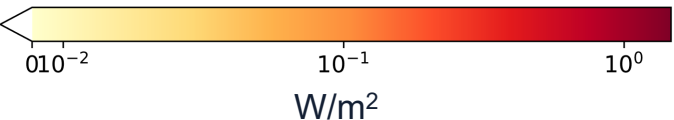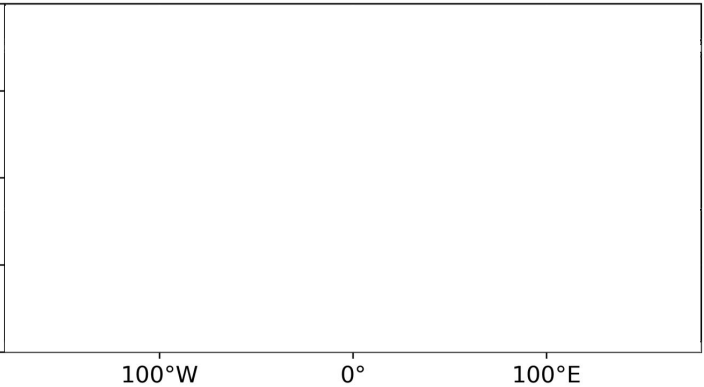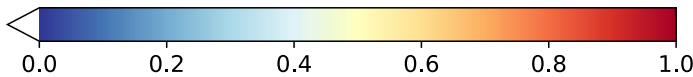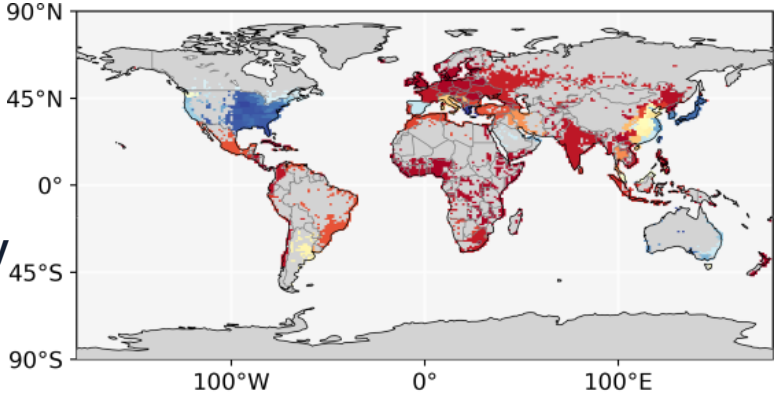   *and*
p_{AC} = present-day

The explicit AC adoption scheme enables global-scale experiments on the effects of changing AC adoption using CTSM.
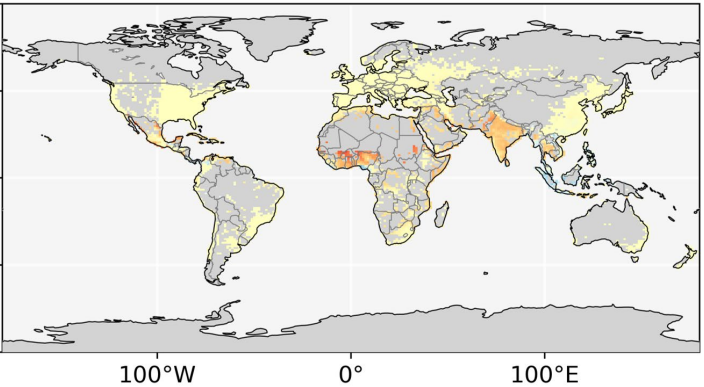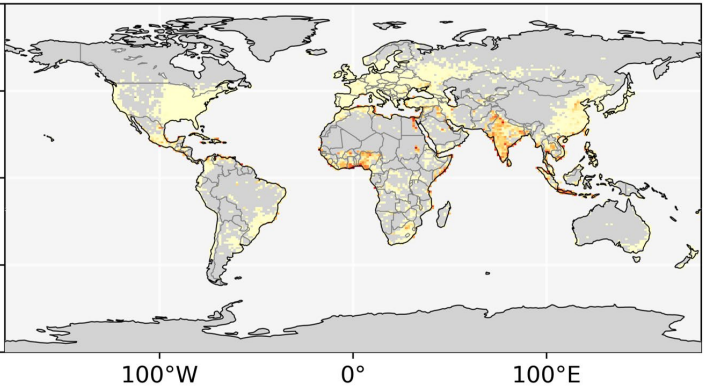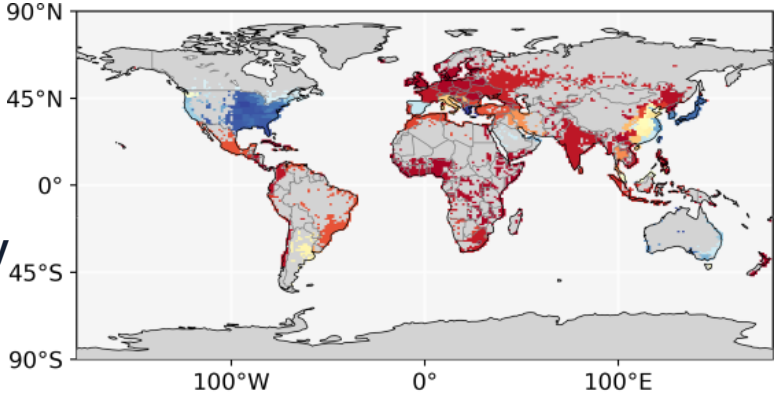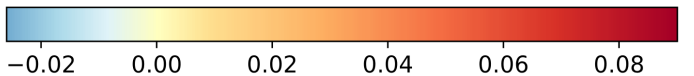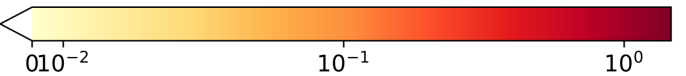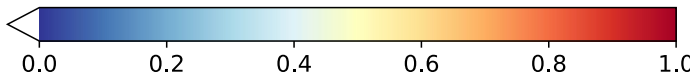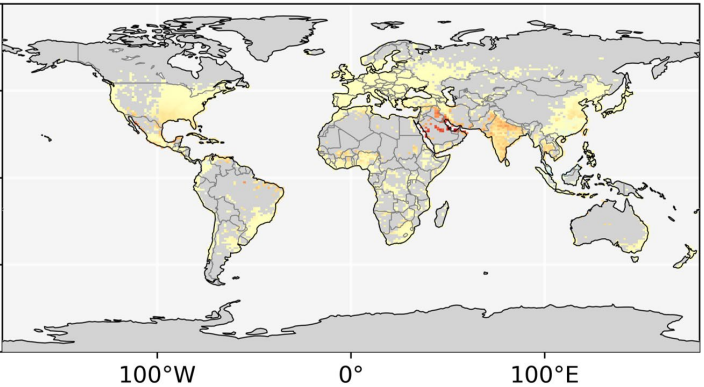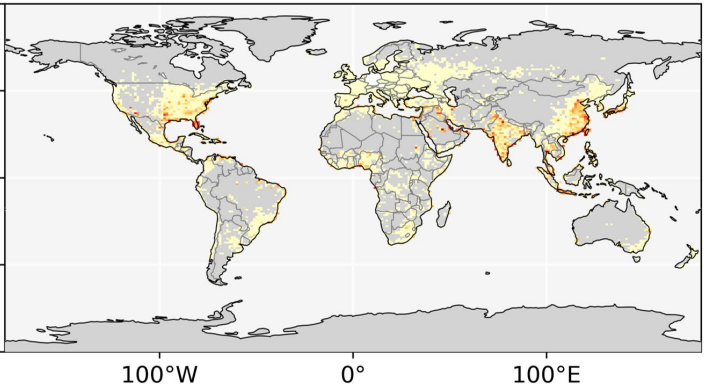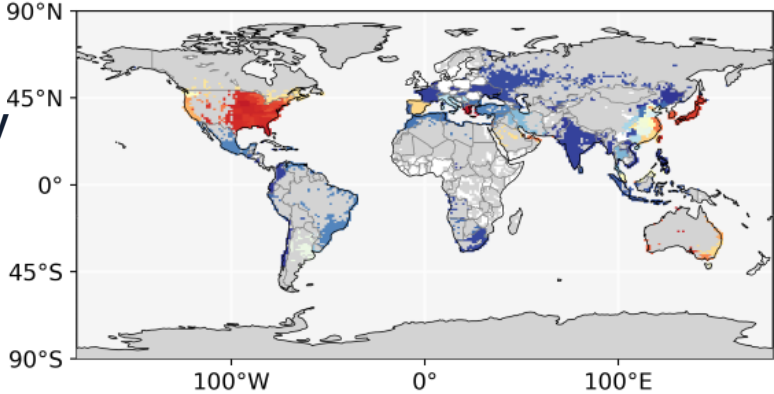

Fig. 8, Li et al. *JAMES* (in press)

These developments enhance CTSM's performance, enable new capabilities, and improve representation of coupled human-urban-Earth dynamics in ESMs.
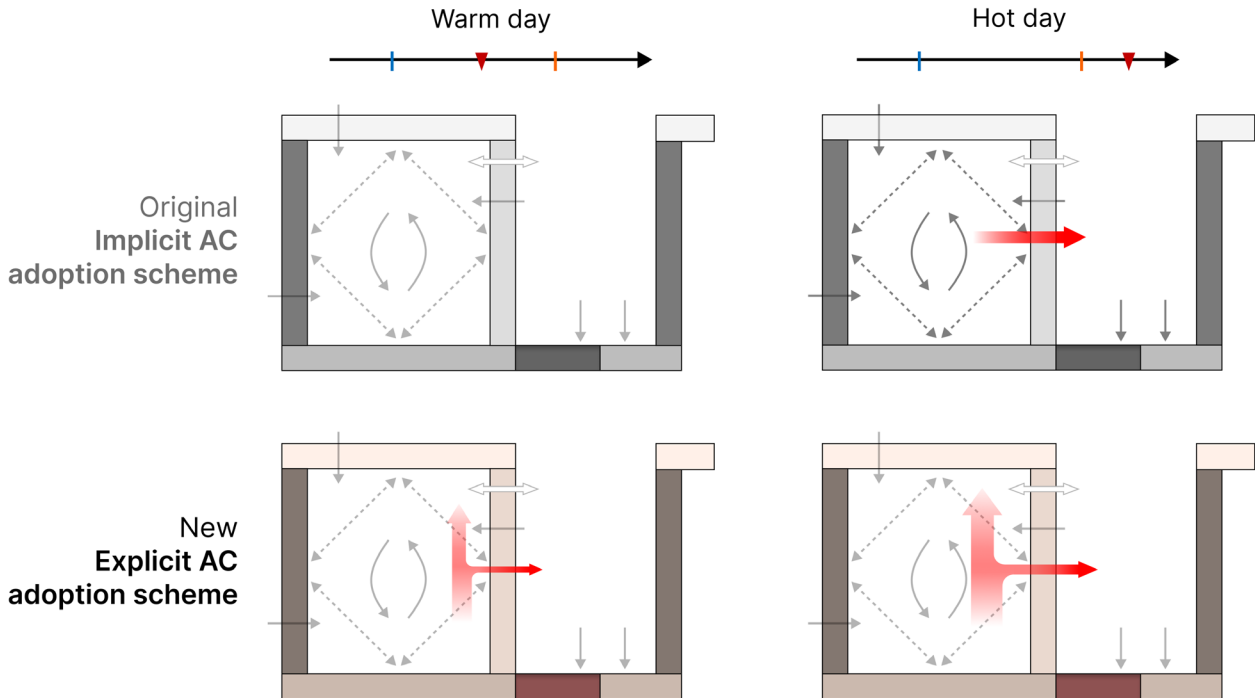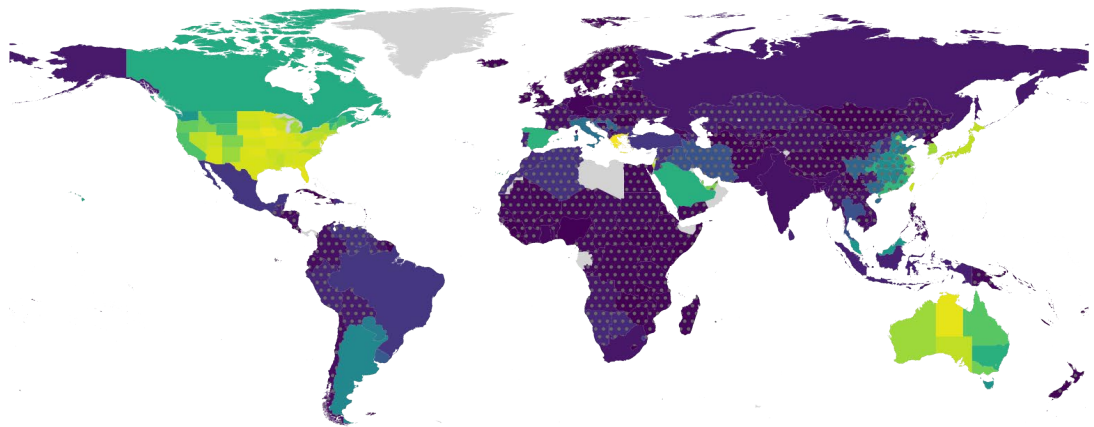
We are working to further enhance the performance and capabilities of BEM in CTSM.

Summer

Outdoor temperature

+

Sensible heat

AC

1

Indoor temperature

+ +

No humidity effect

Winter

Outdoor temperature

Burner

2

Cannot take heat from outside
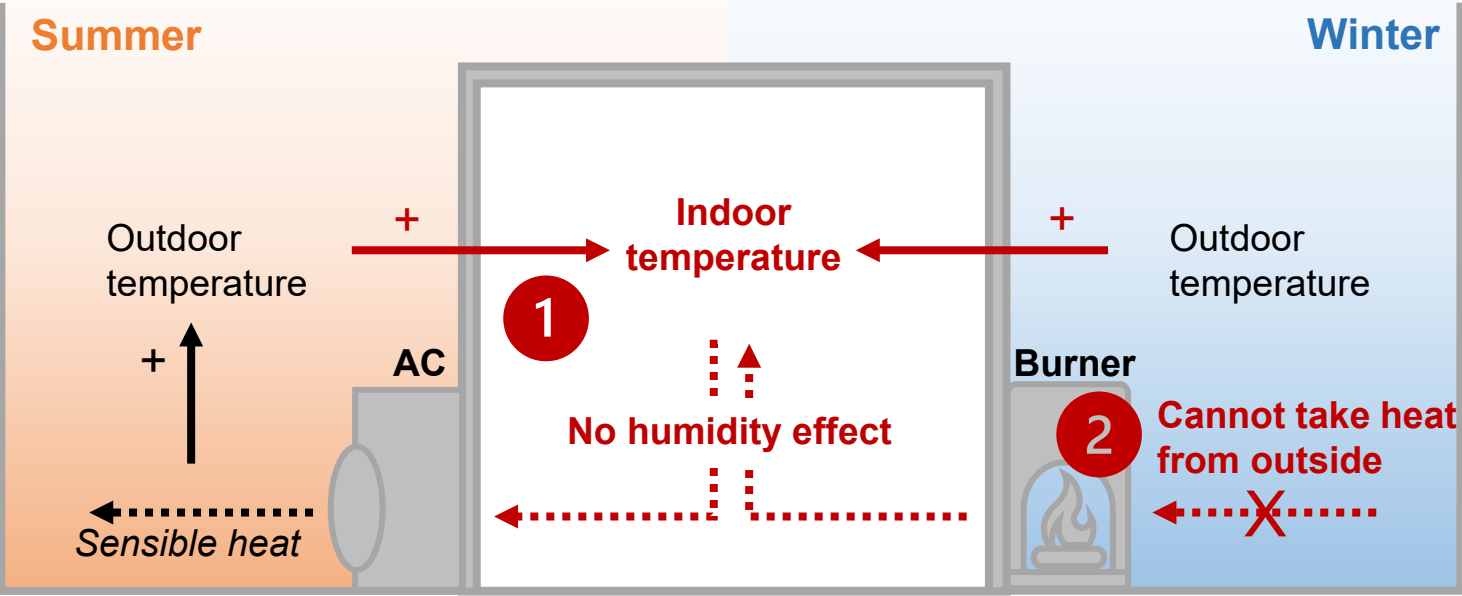
Legend

→ Effects

▸▸▸ Heat transfer processes

1 **Underestimates dehumidification energy demand**

47% More energy is consumed for the same building in a more humid climate

2 **Cannot model winter feedbacks under increased heat pump adoption**

4x More heat pumps in U.S. homes by 2030, pledged by Governors & Biden admin.

We are working to further enhance the performance and capabilities of BEM in CTSM.

Summer

Outdoor temperature & humidity

+

Indoor temperature & humidity

1

AC

+

Sensible heat

Cooling/heating & dehumidification

Winter

Outdoor temperature & humidity

+

ASHP

2

-

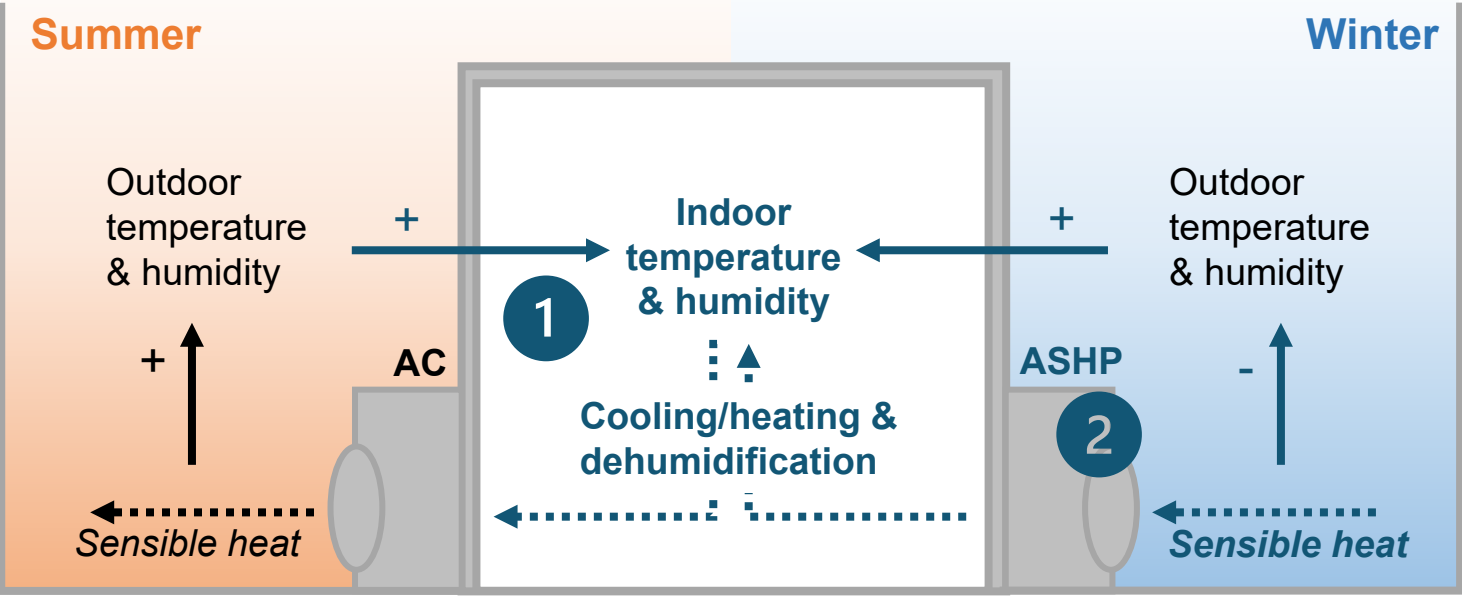**Sensible heat**

Legend

→ Effects

┅► Heat transfer processes

1 **Model indoor latent heat and AC dehumidification energy**

✓ Improved model performance
✓ Indoor & outdoor humid heat exposure

2 **Build unified air source heat pump (ASHP) scheme**

✓ Building electrification scenarios under climate mitigation

Explicitly representing air-conditioning adoption in Earth System Models for global urban modeling
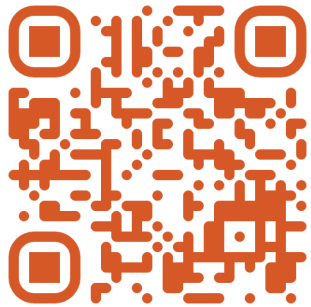
Xinchang 'Cathy' Li[1*], Lei Zhao[1,2,3], Keith Oleson[4], Yuyu Zhou[5], Yue Qin[6], Keer Zhang[7], Bowen Fang[1]

* ✉ xli172@illinois.edu

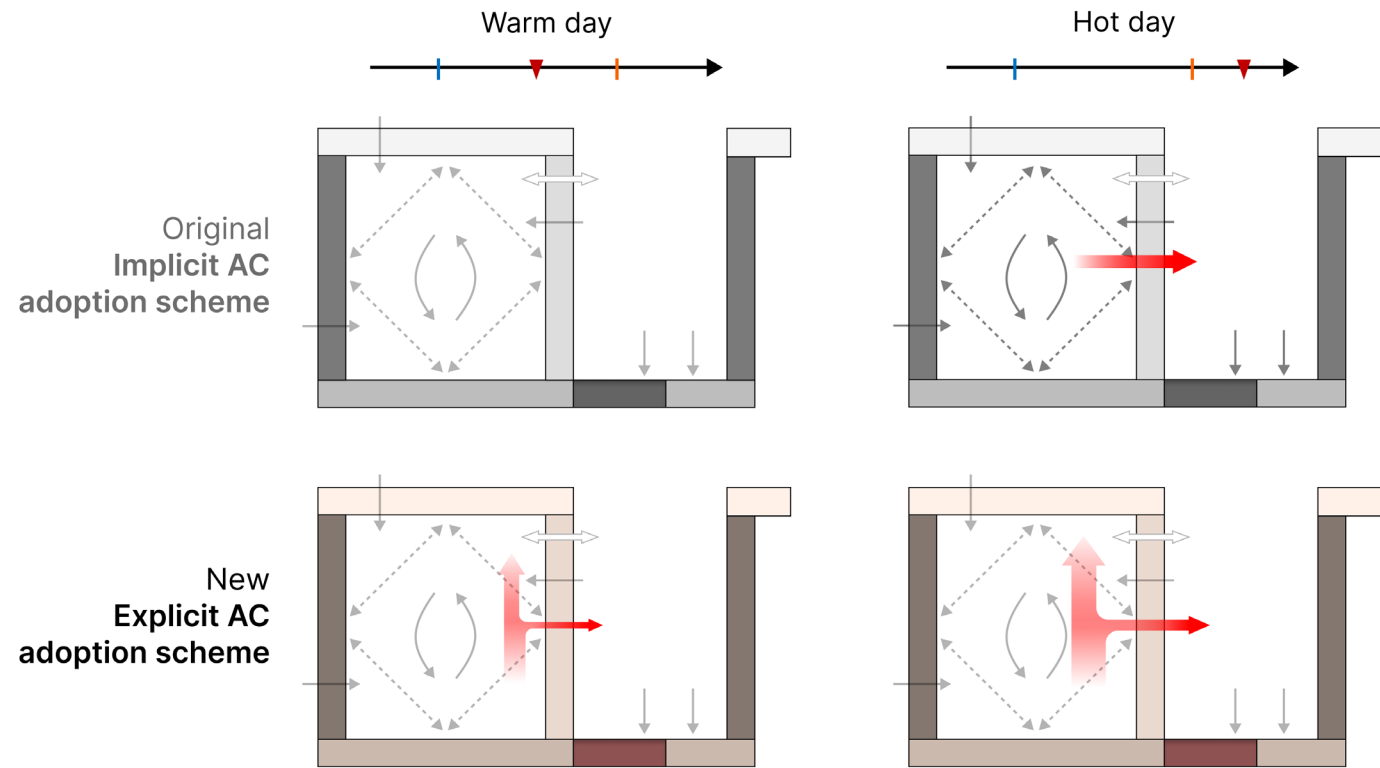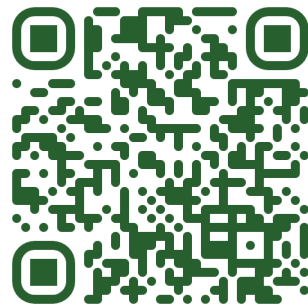⬤ @cathyxinchangli

✕ @CathyXinchangLi

References

Li, X. 'Cathy' *et al*. Enhancing Urban Climate-Energy Modeling in the Community Earth System Model (CESM) through Explicit Representation of Urban Air-conditioning Adoption. *Submitted and in review at Journal of Advances in Modeling Earth Systems. Preprint.* (2023) doi:https://doi.org/10.22541/essoar.169945607.70663662/v1.

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Davis, L., Gertler, P., Jarvis, S. & Wolfram, C. Air conditioning and global inequality. *Global Environmental Change* **69**, 102299 (2021).

Gao, Y., Chan, E. Y. Y., Lam, H. C. Y. & Wang, A. Perception of Potential Health Risk of Climate Change and Utilization of Fans and Air Conditioners in a Representative Population of Hong Kong. *Int J Disaster Risk Sci* **11**, 105–118 (2020).