Nov 17, 2026

2026 CLM Tutorial

Representing urban areas in CESM: The Community Land Model Urban (CLMU)

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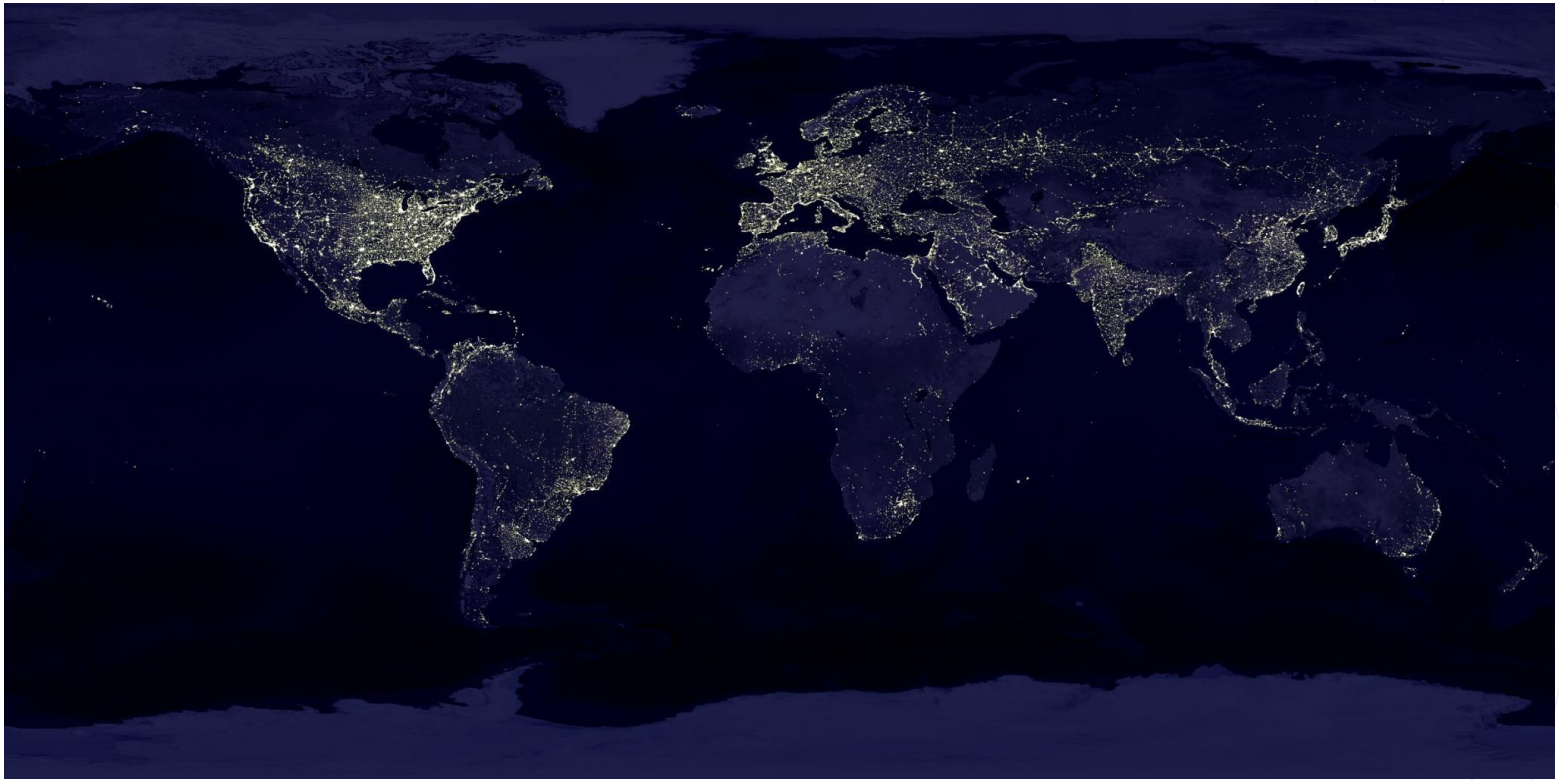
Gordon Bonan, Johannes Feddema, Mariana Vertenstein, Me, Peter Lawrence, Erik Kluzek, Brian Kaufmann, Lei Zhao (Keer Zhang, Xinchang “Cathy” Li, Yifan Cheng, Bowen Fang, Song Jiang, Zhonghua Zheng), Zhonghua Zheng (Yuan Sun, Junjie Yu, Xihan Yao)



Outline

- Why model urban areas?
- What are the features of urban areas that are important to capture in a climate model?
- How are we doing that in CLMU?
- Learn more about CLMU
  - Code
  - References

Satellite view of Earth at night. 1-4% of land surface is urban. More than 50% of world's population lives in urban areas. Projected to increase in the future.



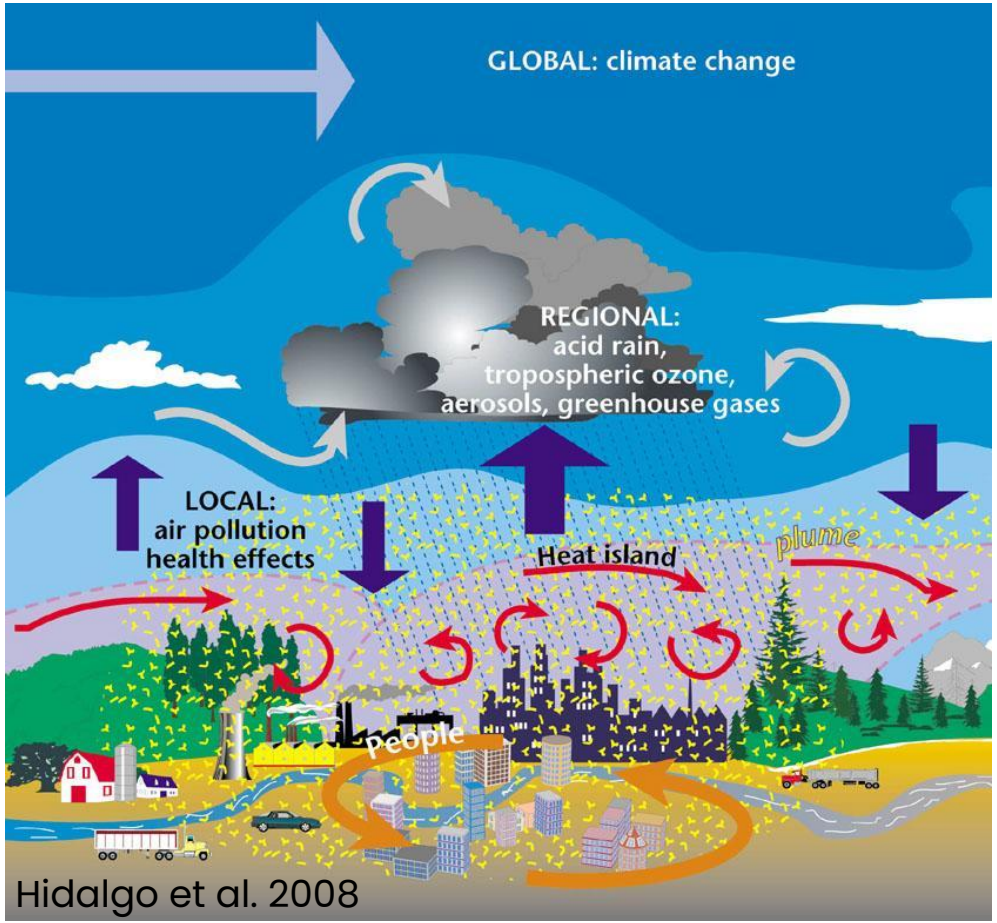
NASA

Manhattan-Mannahatta: on right is a reconstruction of Manhattan Island circa 1609 (called “Mannahatta” by the Lenape native Americans), as compared to today, based on historical landscape ecology and map data.



Markley Boyer / The Mannahatta Project / Wildlife Conservation Society and the aerial view of modern Manhattan, Amiaga Photographers. In: Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network (ARC3) (2011)

Interactions in the Urban Environment at Various Scales



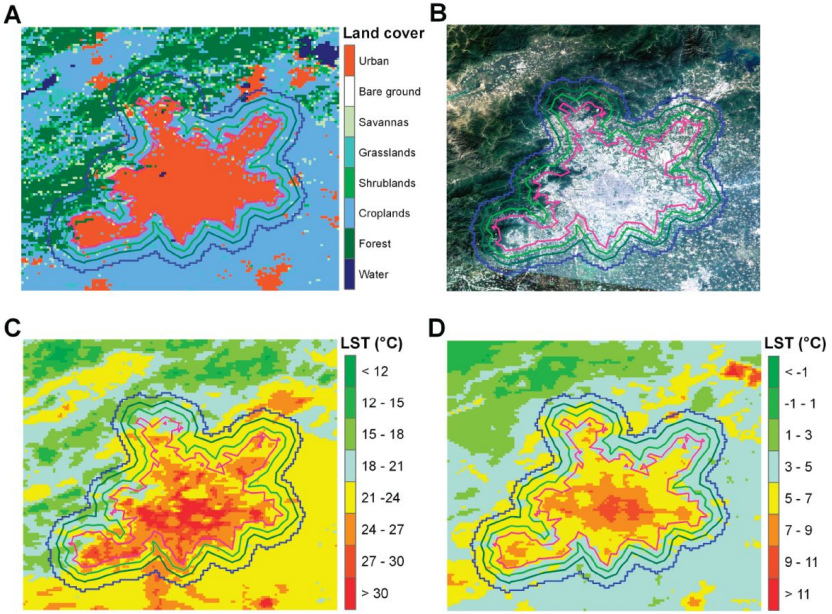
Hidalgo et al. 2008

The built environment is a significant forcing function on the weather climate system because it is:
a heat source (Urban Heat Island),
a poor storage system for water,
an impediment to atmospheric motion,
and a source of aerosols (e.g., pollutants, caused by transportation, energy, and industrial processes with implications for human health and radiative transfer, cloud formation, and precipitation).

Such attributes significantly alter surface energy budgets, the hydrological cycle, and biogeochemical cycles.

The Urban Heat Island (UHI)

- The UHI is defined as the relative warmth of a city compared to the surrounding "rural" (vegetated) areas.
- Typically quantified as the urban air or surface temperature minus the rural air/surface temperature.
- Average air UHI for a mid-latitude city is 1°-3°C but may reach up to 12°C at night under optimal conditions.



Beijing
(A) MODIS data derived land cover/use
(B) Landsat ETM+ true color image with spatial resolution 30 m × 30 m in August, 2005
(C) annual mean daytime land surface temperature (LST) (°C)
(D) annual mean nighttime LST (°C).

Peng et al (2011)

Morphology – Urban canyon, H/W

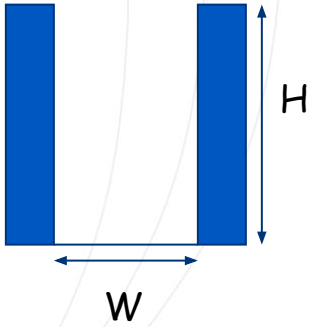




City and residential streets can be characterized by an idealized “canyon” defined by building height H and street width W





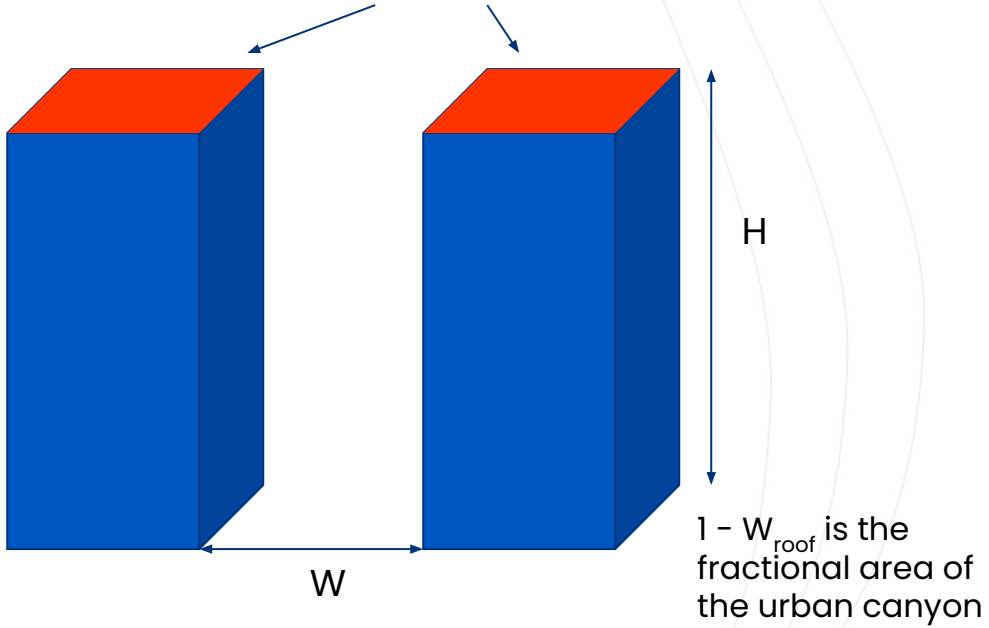


Adapted from G. Bonan

Morphology – Roof area, W_{roof}



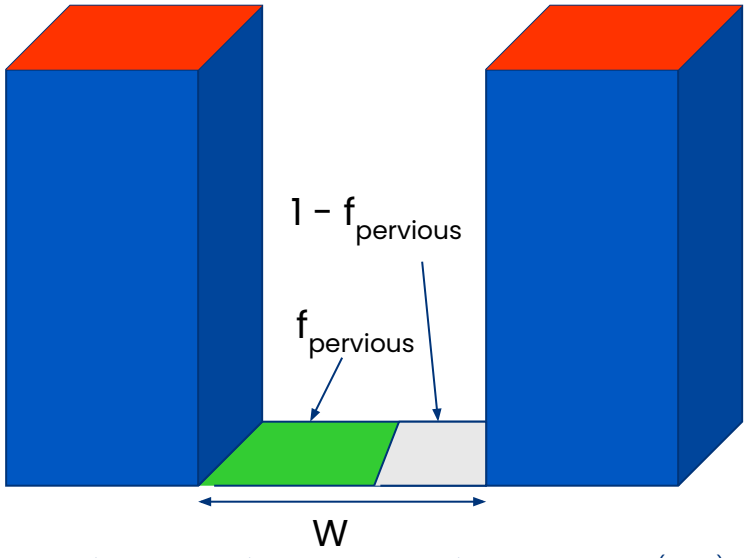
A substantial surface area is covered by roofs



Adapted from G. Bonan

Morphology – Urban greenspace, $f_{pervious}$







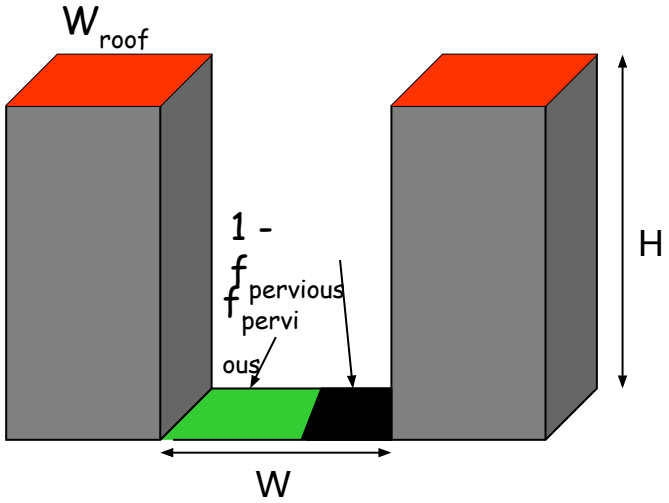


Impervious area = $1 - f_{pervious}$

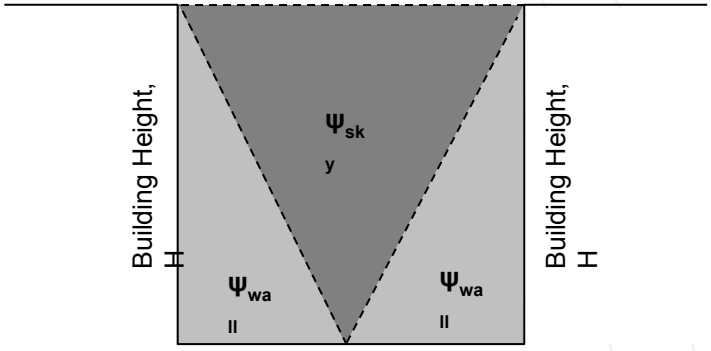
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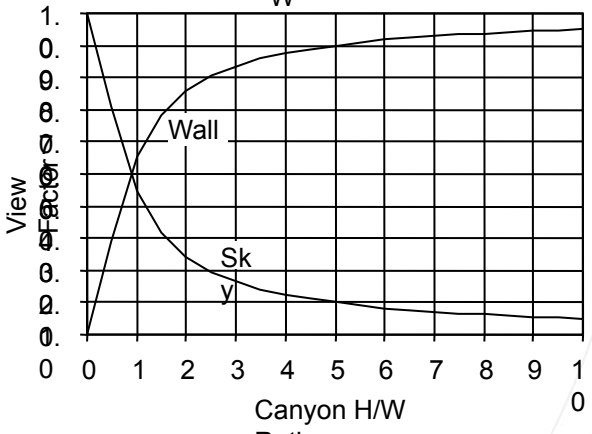
Processes contributing to the UHI

- Decreased surface longwave radiation loss due to reduction of sky view factor



As H/W increases, a point in the street "sees" proportionally less of the sky and more of the wall. More of the longwave radiation emitted by urban surfaces is trapped in the canyon.

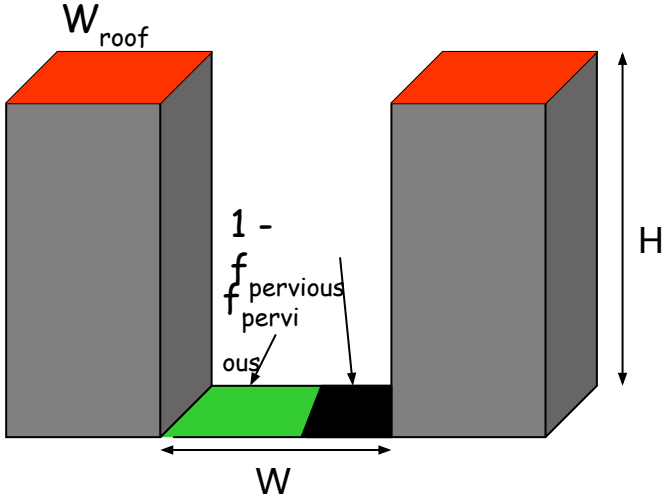


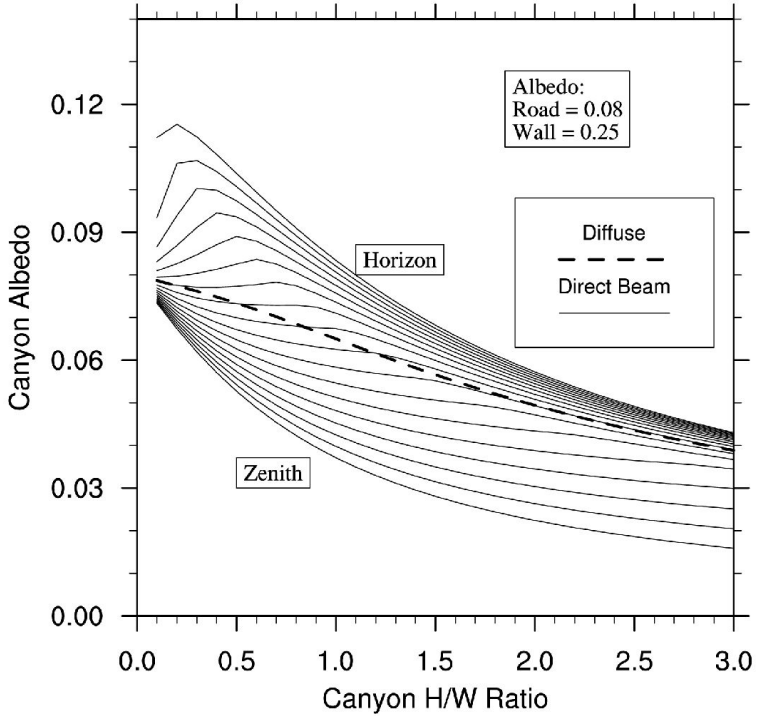


Bonan (2008) Ecological Climatology. 2nd edition

Processes contributing to the UHI

- Increased shortwave absorption due to trapping inside urban canyon (lower albedo)

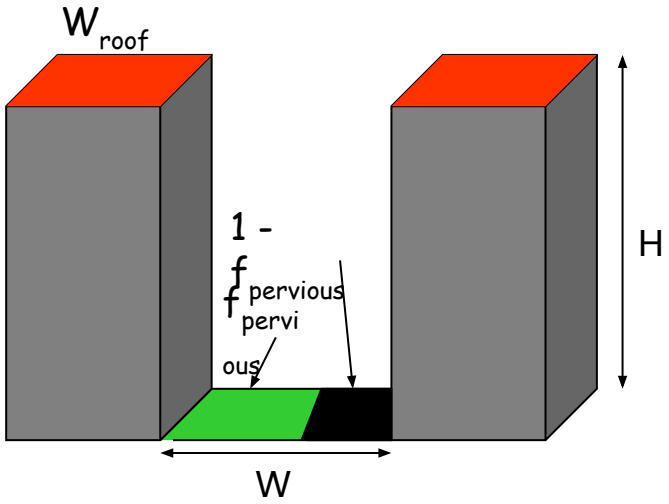




Oleson et al. (2008)

- Direct and diffuse canyon albedo decreases with height to width ratio so that more solar radiation is trapped and absorbed within the canyon.
- Trapping of solar radiation is less effective at larger solar zenith angles. At low H/W, the albedo increases because the higher albedo walls dominate the radiative exchange.

Processes contributing to the UHI

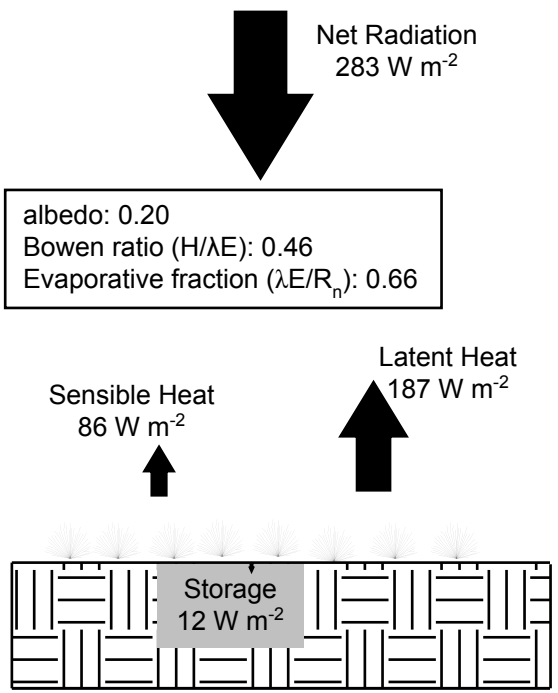


- Reduction of ET due to replacement of vegetation with impervious surfaces
- Increased storage of heat due to larger heat capacity of urban materials
- Reduced turbulent transfer of heat due to reduced wind within canyon

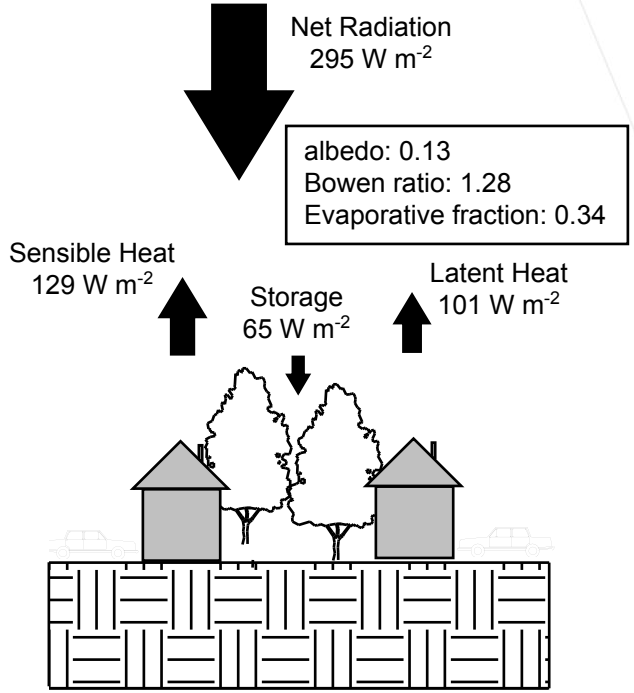
Processes contributing to the UHI

Observed surface energy fluxes, Vancouver, B.C.; average summer day

Cleugh & Oke (1986)



Rural: managed grassland

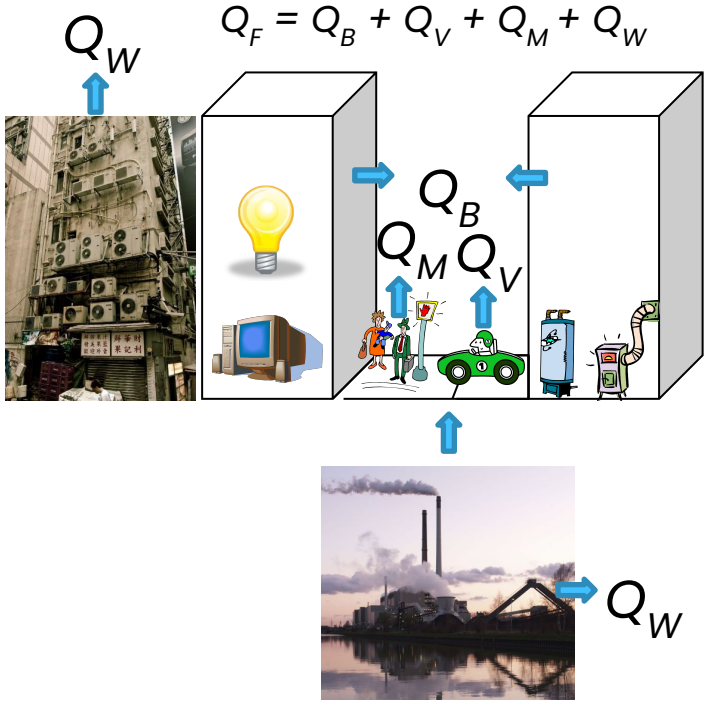


Suburban: 25% building, 11% paved, 64% greenspace

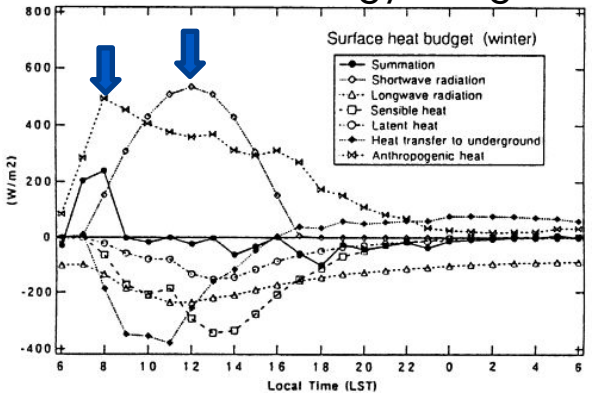
Figure courtesy G. Bonan

Processes contributing to the UHI

- Anthropogenic sources of heat (Heat released to the atmosphere as a result of human activities)

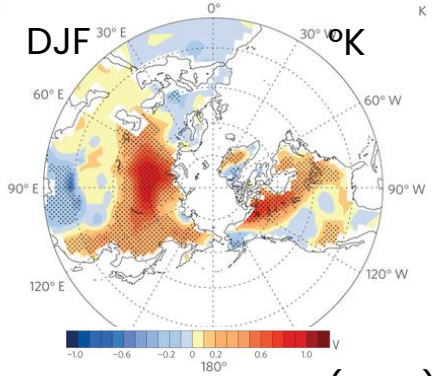


Winter surface energy budget in central Tokyo



Ichinose et al. (1999)

Mean surface air temperature difference

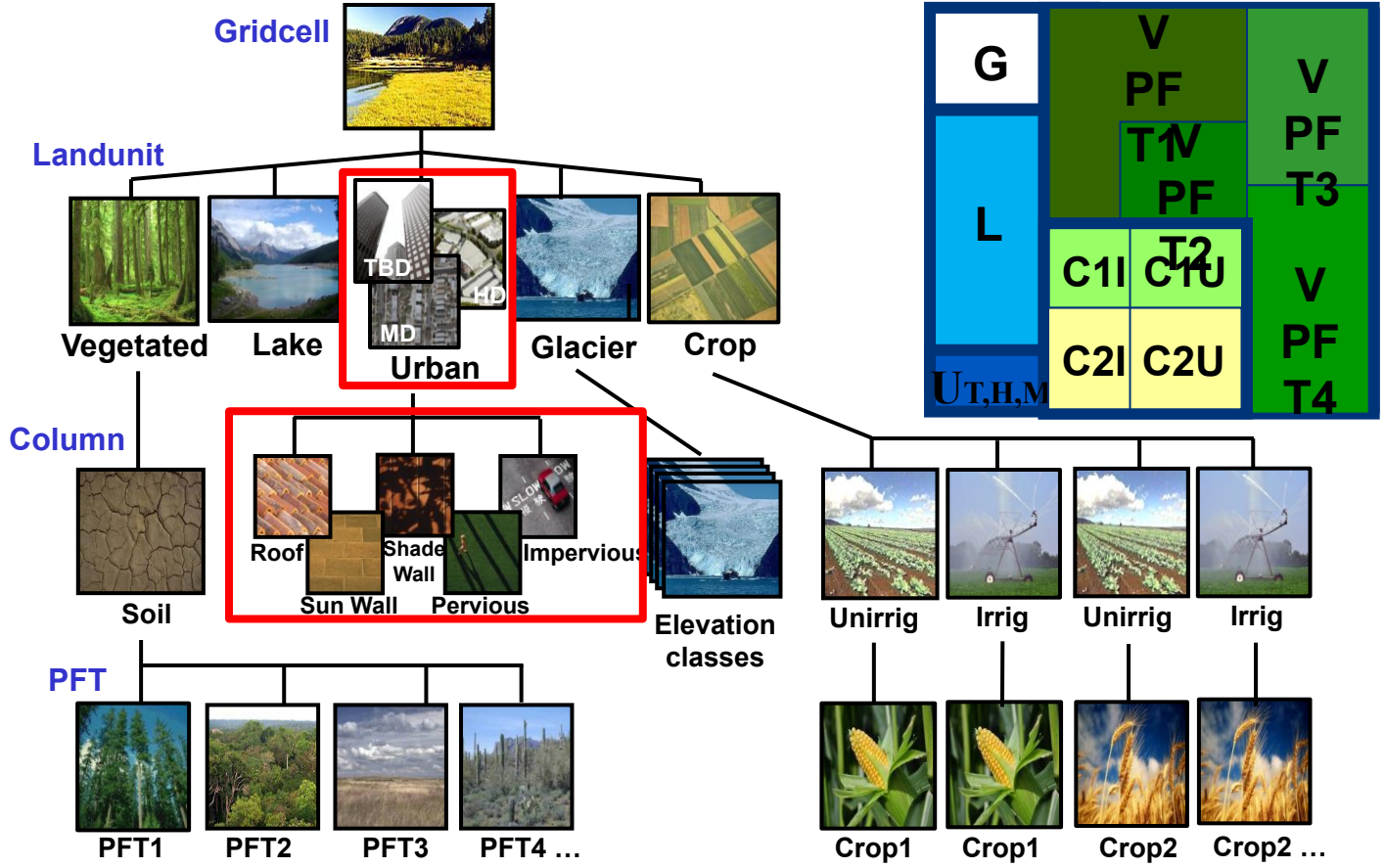


Zhang et al. (2013)

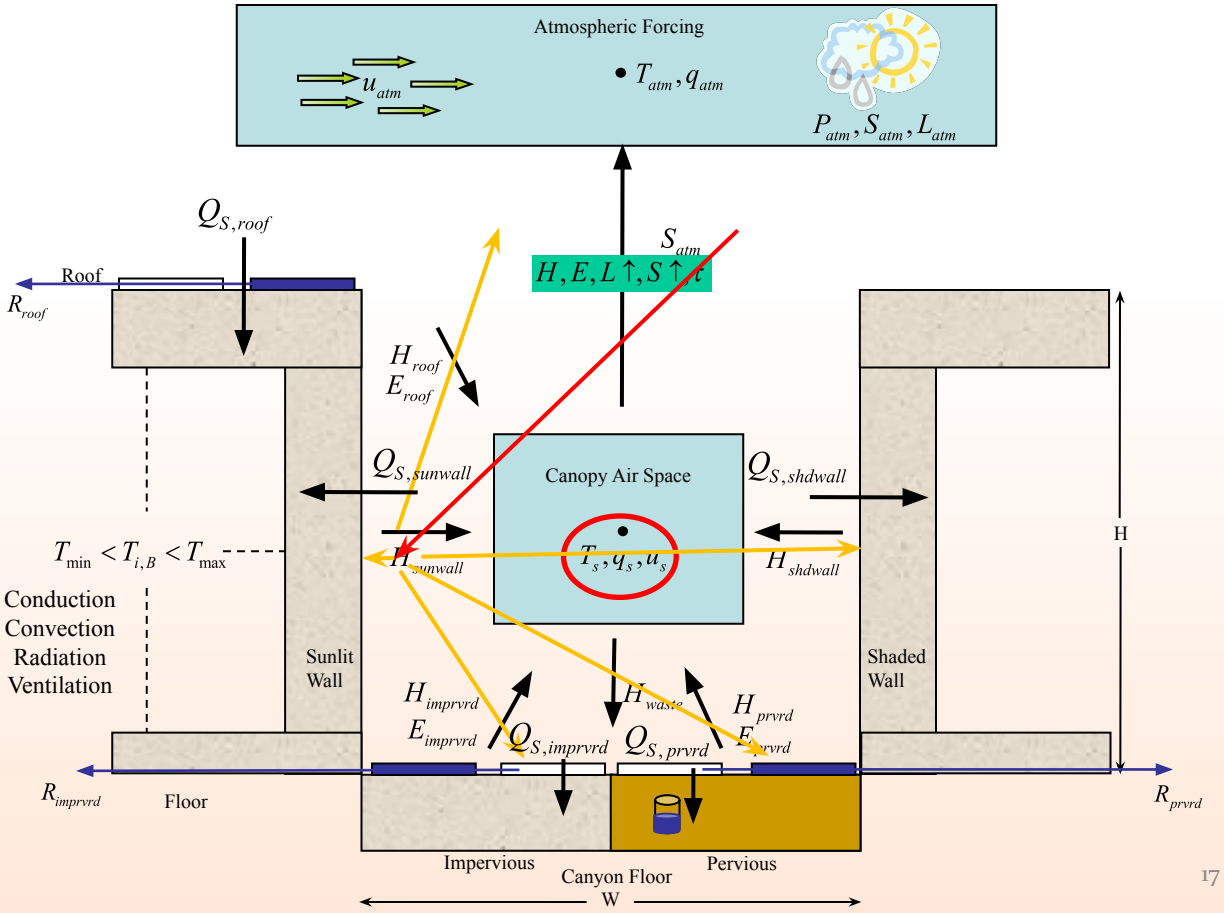
Processes contributing to the UHI – Summary

- Decreased surface longwave radiation loss due to reduction of sky view factor
- Increased shortwave absorption due to trapping inside urban canyon (lower albedo)
- Reduction of ET due to replacement of vegetation with impervious surfaces
- Increased storage of heat due to larger heat capacity of urban materials
- Reduced turbulent transfer of heat due to reduced wind within canyon
- Anthropogenic sources of heat (heating, air conditioning, wasteheat, traffic, metabolic heat)

Incorporating urban areas into CLM

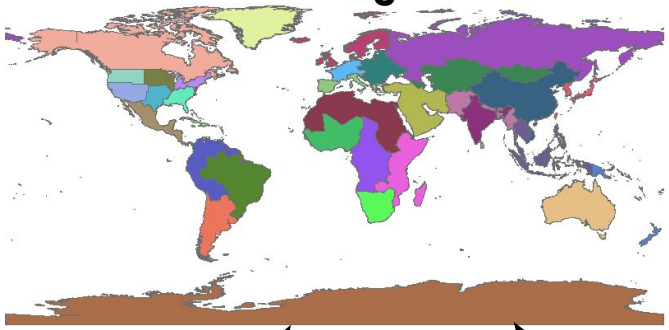


Community Land Model Urban



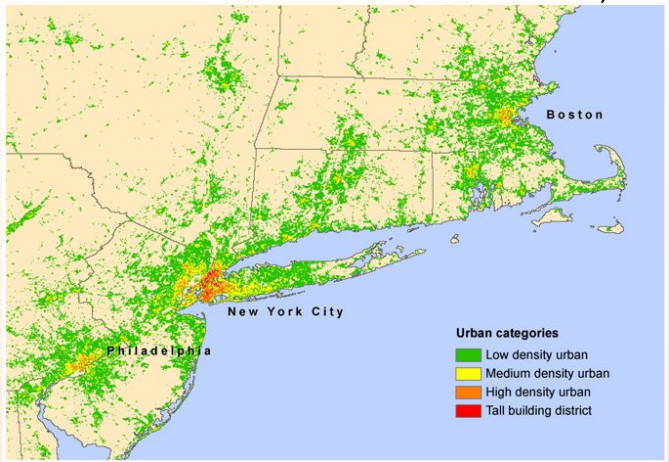
Global Urban Characteristics Dataset

Global Regions



→ **To CLMU**

Urban Extent - Landscan 2004



Urban Properties – Compilation of building databases

Morphological
- ***Building Height***
- ***H/W ratio***
- ***Pervious fraction***
- ***Roof fraction***

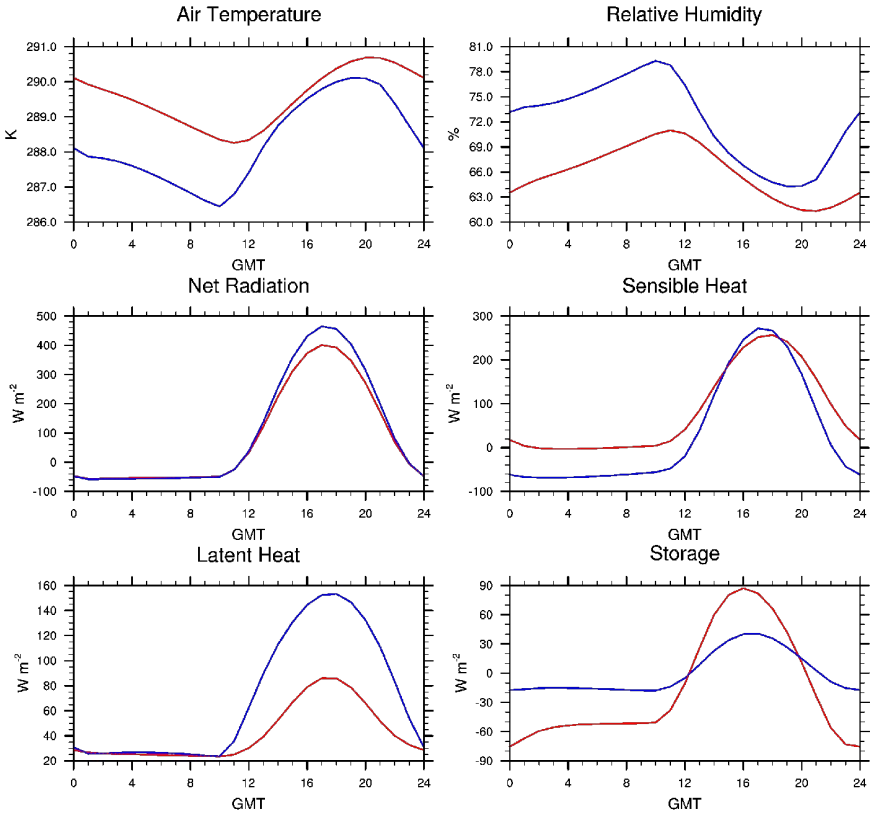
Radiative – Roof/Wall/Road
- ***Albedo***
- ***Emissivity***

Thermal – Roof/Wall/Road
- ***Conductivity***
- ***Heat Capacity***

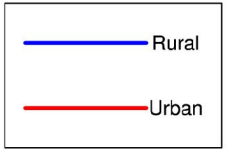
Interior temperature settings (HAC)

Jackson et al. 2010
Oleson and Feddema 2020

Modeled Urban and Rural Energy Balance



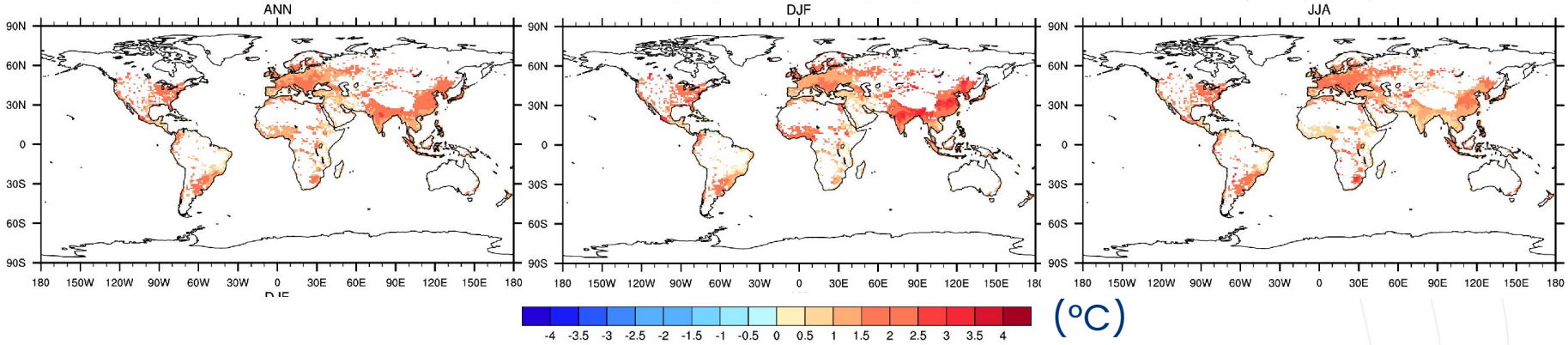
Annual Average Diurnal Cycle



- Urban area stores more heat during daytime and releases heat at night resulting in nighttime heat island
- Urban has lower latent heat due to impervious surfaces which contributes to heat island

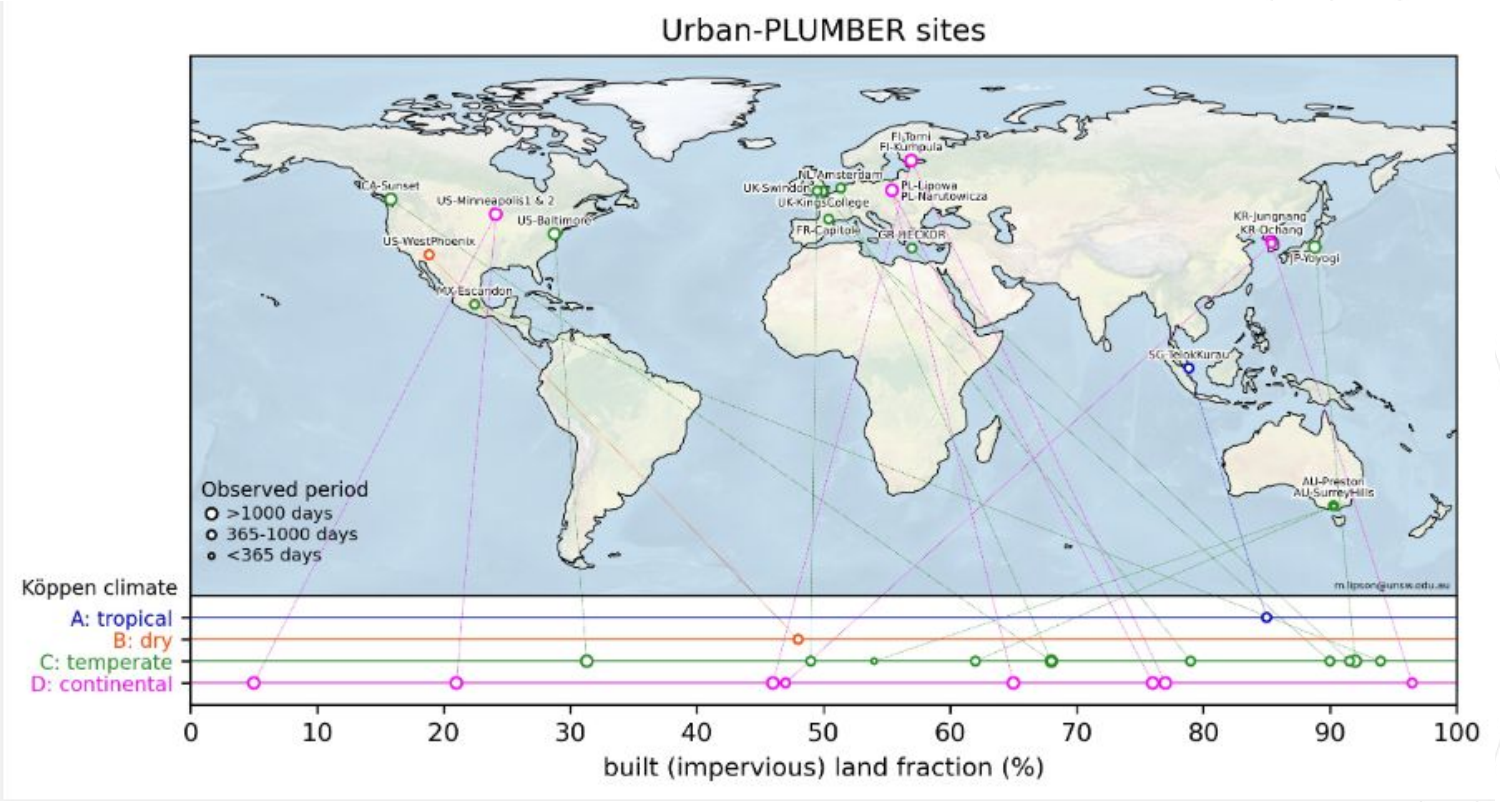
Modeled Heat Island (Urban minus Rural air temperature)

ANN DJF JJA



- Heat island positive almost everywhere, ranges from near-zero up to 4°C
- Spatial/seasonal variability in the heat island caused by urban to rural contrasts in energy balance and response of these surfaces to seasonal cycle of climate

Model Evaluation – Urban-PLUMBER flux tower sites

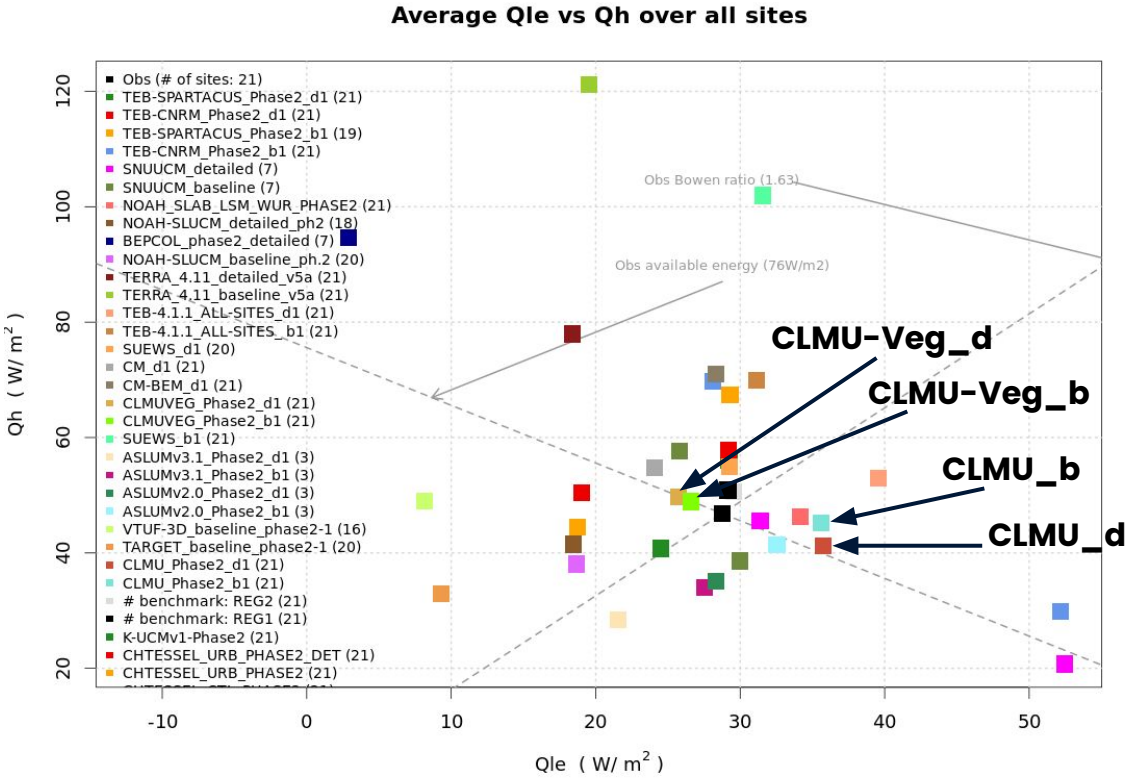


Lipson et al. (2022)

Model Evaluation – Urban-PLUMBER flux tower sites

- 21 Tower Sites
- “b” - baseline
- “d” - detailed
- CLMU - urban canyon with integrated “vegetation”
- CLMU-Veg - urban canyon + separate pft tiles

Courtesy modelevaluation.org. Preliminary!



Recent Updates to CLMU

- Improved urban properties: Oleson and Feddema (2020), modifies Jackson et al. (2010)
- Dynamic urban capability - changes in urban extent over time (Fang et al. 2026)
- New urban extent; Gao and O'Neill (2020) (2000-2100; CTSM5.3), LUH3/CMIP7 (1850-2100; CTSM5.5), replaces static circa-2000 Jackson et al. (2010)
- Explicit AC adoption: Li et al. (2023)
- Indoor humidity and AC dehumidification (Li et al. (2026)
- Local Climate Zones (LCZs; up to 10 classes per gridcell; Sun et al. 2025; in progress)
- CLMU-Tree, replaces pervious canyon floor (K. Zhang, in progress)
- U-Surf, a global 1km spatially continuous urban surface property dataset (Cheng et al. (2025, 2026); in progress)

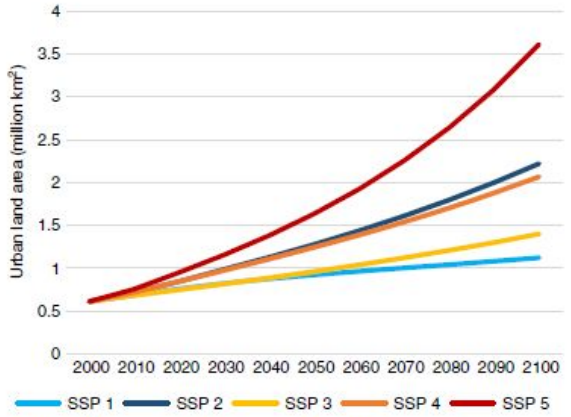


Fig. 1 Global total amount of urban land under different scenarios over the 21st century. The scenarios correspond to the five Shared Socioeconomic Pathways (SSPs 1-5): sustainability, middle of the road, regional rivalry, inequality, and fossil-fueled development.

U-Surf – A global 1km urban properties dataset

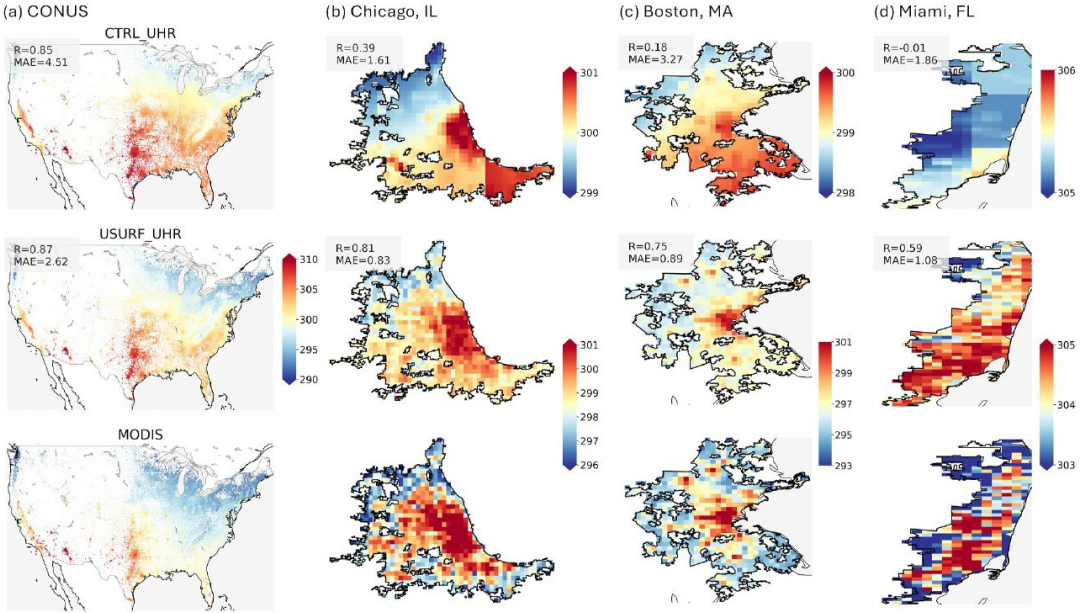


Figure 3. Five-year (2010–2014) summertime average urban land surface temperature comparison between CTRL (top row), USURF (middle row) land-only CESM simulations and MODIS observations (bottom row) at 0.03125° × 0.03125° resolution. The performance metrics correlation coefficient (R) and mean absolute error (MAE) [K] are demonstrated in (a) CONUS and selected U.S. cities: (b) Chicago, IL, (c) Boston, MA, (d) Miami, FL, only using common urban pixels. The city boundary shapefiles are from the U.S. Census Bureau (2024). Panel (a) shares a common colorbar. In panels (b–d), CTRL uses separate colorbars due to its narrower spatial distribution; while USURF and MODIS share the same colorbars for spatial pattern comparison.

Cheng et al. (2026)

Global urban modeling – caveats and limitations

- Idealized cities
  - Inadequacies of the urban canyon model in representing complex urban surfaces both within a city and between cities. Lack of accurate and spatially explicit urban morphological, thermal, and radiative properties (although the new 1km dataset is a tremendous advancement).
- Coarse climate model spatial resolution
  - Mesoscale features not captured (heat island circulation)
  - Urban and rural areas forced by same climate (e.g., no boundary layer heat island or pollution, or precipitation differences)
  - Individual cities generally not resolved, urban areas are highly averaged representation of individual cities
  - Urban fluxes affect only local, not regional/global climate (minimal feedbacks)
- Future urban form and function
  - For future climate scenarios, we can now account for changes in urban extent, but we do not account for how urban areas in form (e.g., changes in H/W) will change to accommodate overall growth in population and the projected increase in urban dwellers and how this will affect and interact with the climate and heat stress in cities
- Lack of explicit urban vegetation (but hopefully alleviated with CLMU-Tree)
- Anthropogenic heat flux
  - Highly simplified representations of HAC processes. Other sources of anthropogenic heat such as those due to internal heat gains (e.g., lighting, appliances, people), traffic, human metabolism, as well as anthropogenic latent heat are not represented.
- No BGC components included (carbon, nitrogen, aerosols, ozone, etc.)

Community Land Model Urban – Code (/src)

- main/initGridCellsMod.F90: initialize landunits
- main/initVerticalMod.F90: initialization for wall and roof layers and interfaces
- main/clm_varcon.F90: parameters, e.g, building energy model constants
- main/subgridAveMod.F90: scaling to landunit/gridcell level
- biogeophys/UrbanParamsType.F90: read in input data and namelist items, compute view factors and aerodynamic parameters
- cpl/share_esmf/UrbanTimeVarType.F90: initialize and interpolate time-varying data (minimum interior building temperature)
- biogeophys/UrbanAlbedoMod.F90: albedo
- biogeophys/UrbanFluxesMod.F90: canyon turbulent/momentum fluxes, heat stress indices
- biogeophys/UrbanRadiationMod.F90: radiation
- biogeophys/UrbBuildTempOleson2015Mod.F90: interior building temperature/humidity solution
- biogeophys/SoilTemperatureMod.F90: roof/wall/road temperatures
- biogeophys/SoilFluxesMod.F90: “ground heat” fluxes
- biogeophys/SoilHydrologyMod.F90, etc.: hydrology
- Search for, e.g., icol_roof, isturb_tbd, isturb_hd, isturb_md

CLMU References

- **Chapter 2.16 of the Technical Note for the latest development code: https://escomp.github.io/CTSM//tech_note/index.html**.
- Sun, Y., K.W. Oleson, C. He, and Z. Zheng, 2026: Advancing CLMU for regional urban climate simulations through WRF coupling: intercomparison with NOAH-SLUCM, JAMES, submitted.
- Yu, J., J. S. Schreck, D. J. Gagne, K. W. Oleson, J. Li, Y. Liang, Q. Liao, M. Sun, and D. O. Topping, 2026: Reinforcement Learning Heating Control under Two-Way Interactions between Building Energy Use and Urban Climate, Energy and Buildings, submitted.
- Fang, B., L. Zhao, K. Oleson, K. Zhang, P. Lawrence, B. Sacks, C. Cao, C. He, Q. Huang, Z. Liu, and X. Lee, 2026: Representing dynamic urban land change in the Community Earth System Model (CESM), JAMES, in revision.
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- Li, X., L. Zhao, Z. Luo, K. Oleson, Y. Cheng, X. Xie, A.C.G. Varquez, and M. Sekiya, 2026: Divergent humidity-driven growth in urban air-conditioning energy demand under climate change, Nature Cities, https://doi.org/10.1038/s44284-026-00474-4.
- Cheng, Y., L. Zhao, K. Oleson, T.C. Chakraborty, K. Zhang, C. He, and J. Yang, 2026: Importance of spatially continuous urban surface properties in urban-resolving Earth system modeling, JAMES, 18, e2025MS005573, https://doi.org/10.1029/2025MS005573.
- Sun, Y., K.W. Oleson, and Z. Zheng, 2026: Modeling urban traffic heat flux in the Community Earth System Model: Formulation and validation for two test sites. JAMES, 18, e2025MS005435, https://doi.org/10.1029/2025MS005435.
- Sun, Y., K.W. Oleson, L. Zhao, G. Mills, C. He, M. Demuzere, D. Topping, N. Zhang, and Z. Zheng, 2025: Enhancing global-scale urban land cover representation using local climate zones in the Community Earth System Model, JAMES, https://doi.org/10.1029/2025MS004934.
- Yu, J., Z. Zheng, S. Lindley, L. Zhao, C. Wang, Q. Wu, L. Li, D.O. Topping, J.S. Schreck, D.J. Gagne, and K.W. Oleson, 2025: Leveraging automated machine learning (AutoML) for urban climate emulation, Big Data and Earth System, https://doi.org/10.1016/j.bdes.2025.100040.

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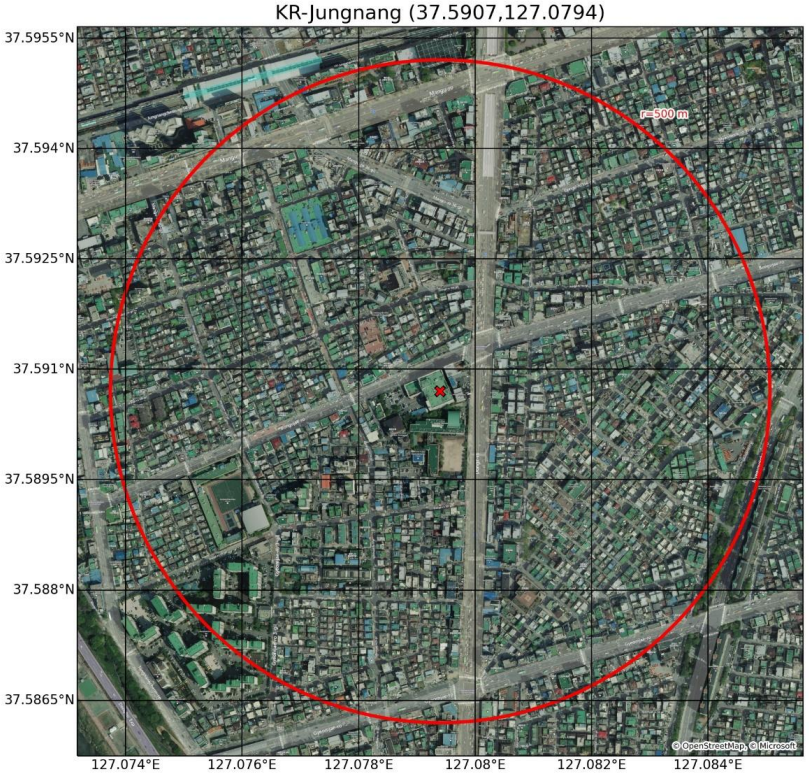
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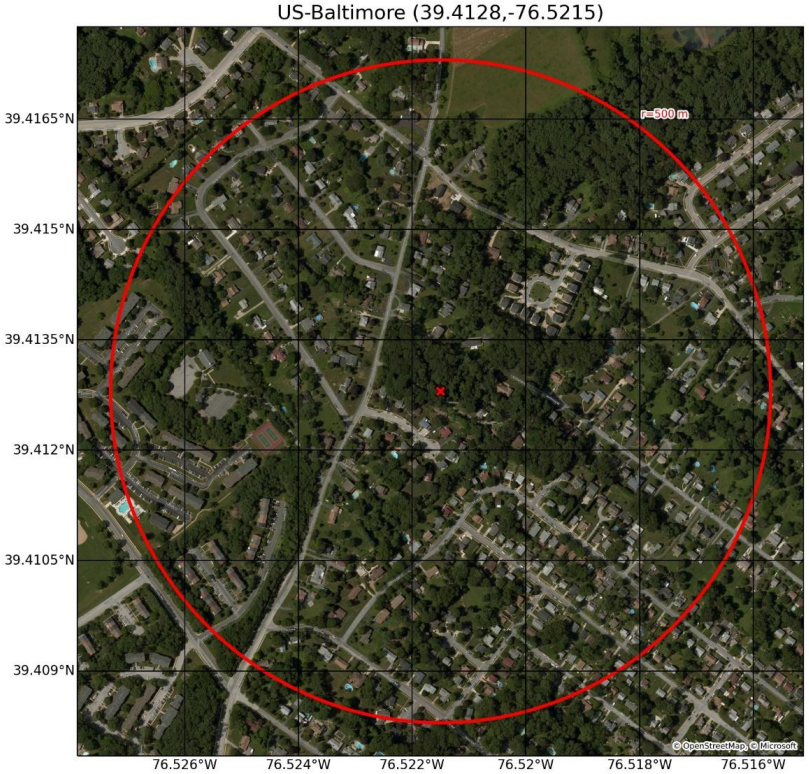
Community Land Model Urban

Thank You!

Questions?

Model Evaluation – Urban-PLUMBER flux tower sites





https://doi.org/10.22647/EAPL-OC_JN2021

Crawford et al. (2011)

U-Surf – A global 1km urban properties dataset

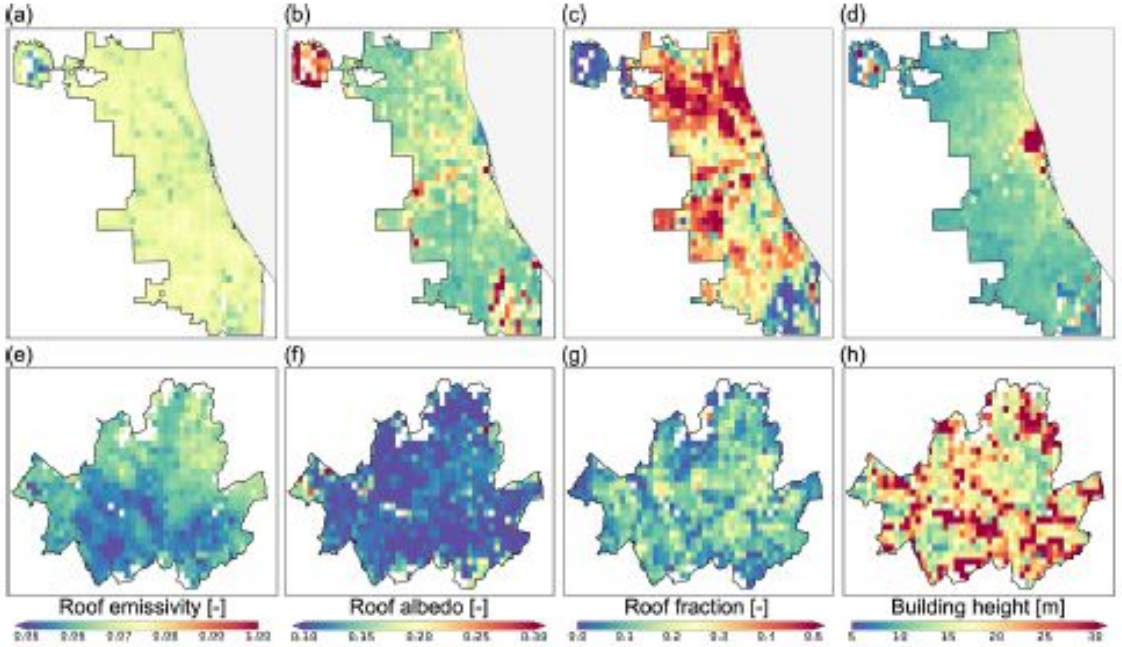


Figure 6. Spatial distributions of roof emissivity (–), roof albedo (–), roof fraction (–), and building height (m) in **(a–d)** Chicago, USA, and **(e–h)** Seoul, South Korea. Each pair of panels within the same column shares a consistent color scale.

Cheng et al. (2025)

Community Land Model Urban

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