

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

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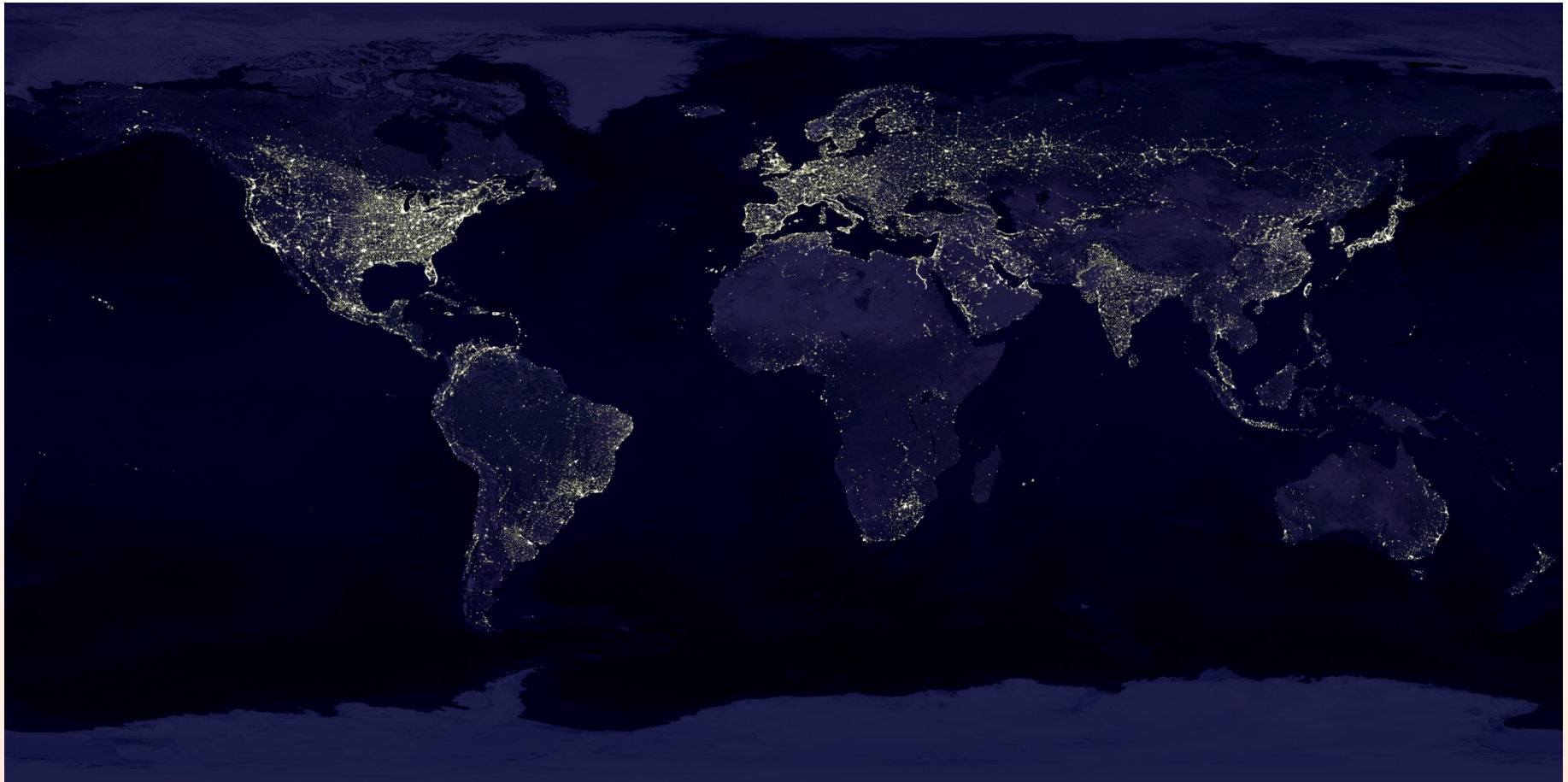
Terrestrial Sciences Section (TSS)

Climate and Global Dynamics (CGD) Laboratory



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

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

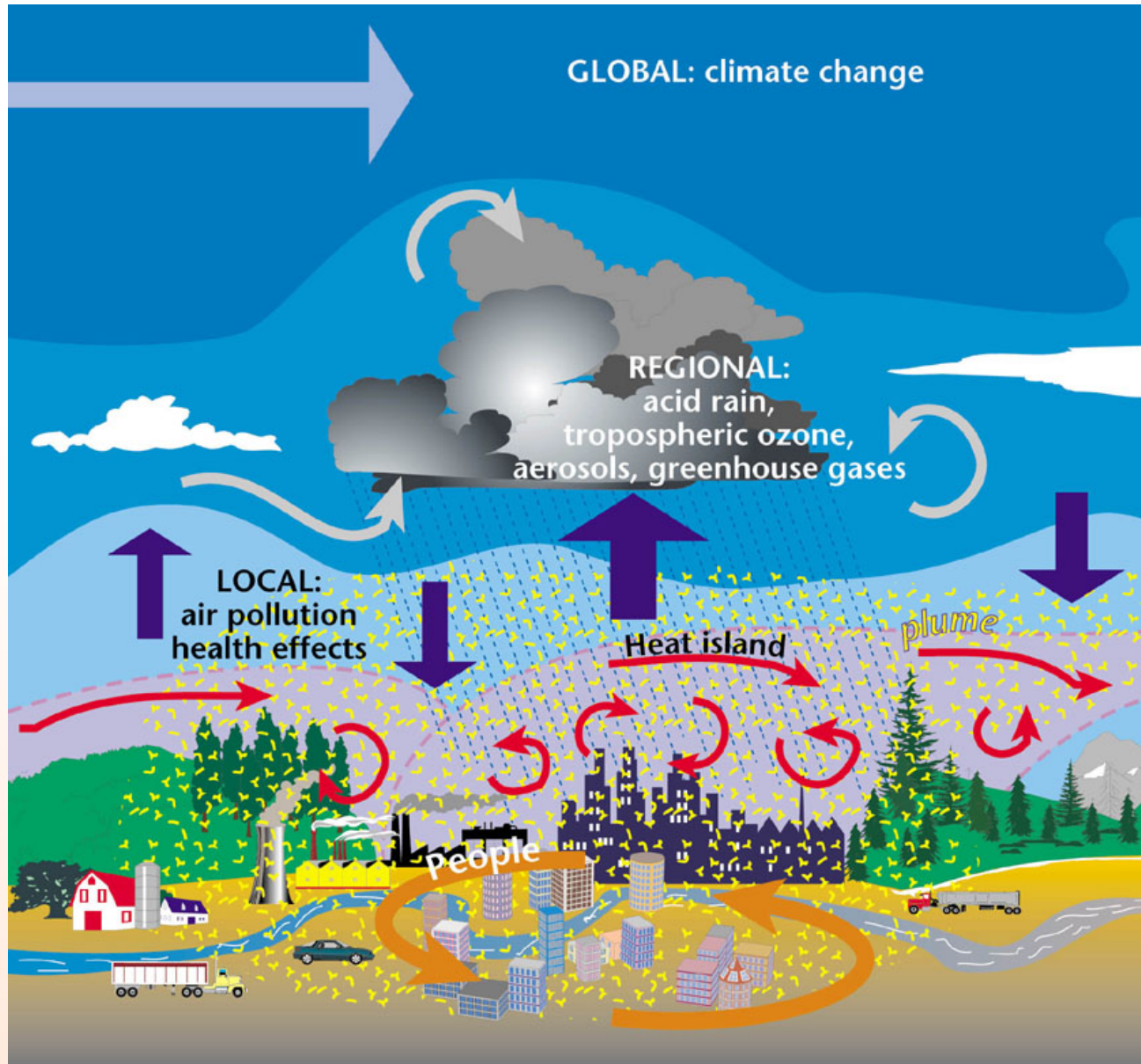


Manhattan-Mannahatta: on right is a reconstruction of Manhattan Island circa 1609 (called “Mannahatta” by the Lenape native Americans), as compared to today, based on historical landscape ecology and map data.



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)

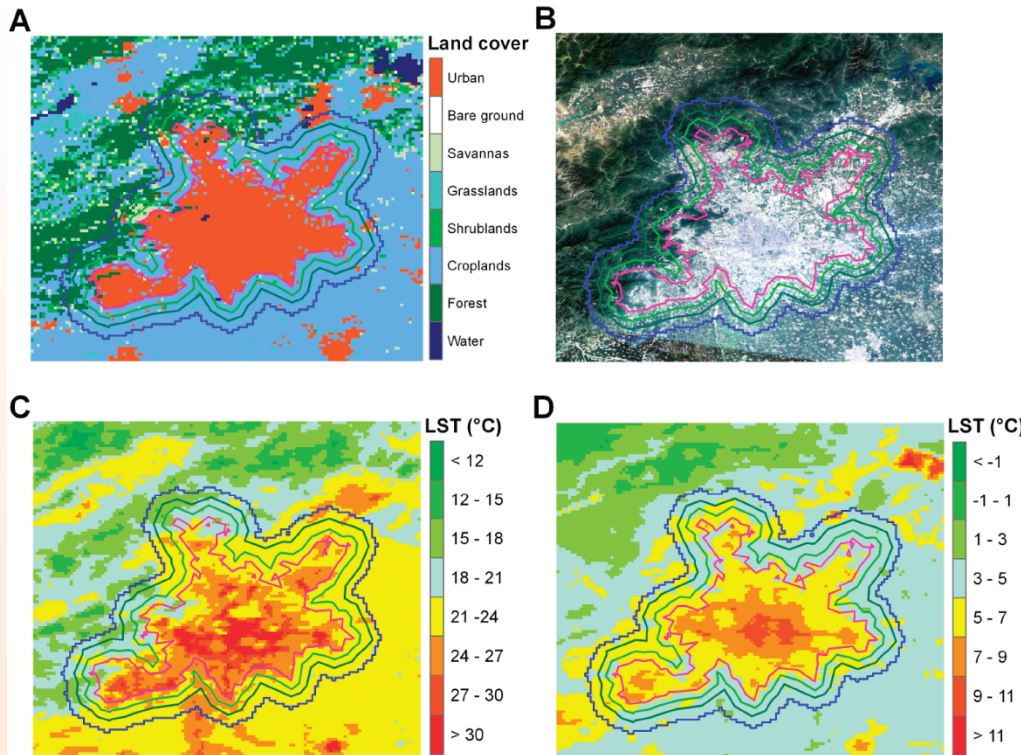
Interactions in the Urban Environment at Various Scales



Hidalgo et al. 2008

The 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 $30\text{ m} \times 30\text{ m}$ in August, 2005

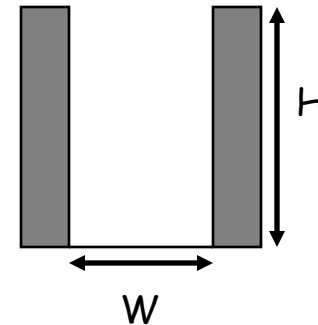
(C) annual mean daytime land surface temperature (LST) ($^{\circ}\text{C}$)

(D) annual mean nighttime LST ($^{\circ}\text{C}$).

Urban canyon, H/W



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

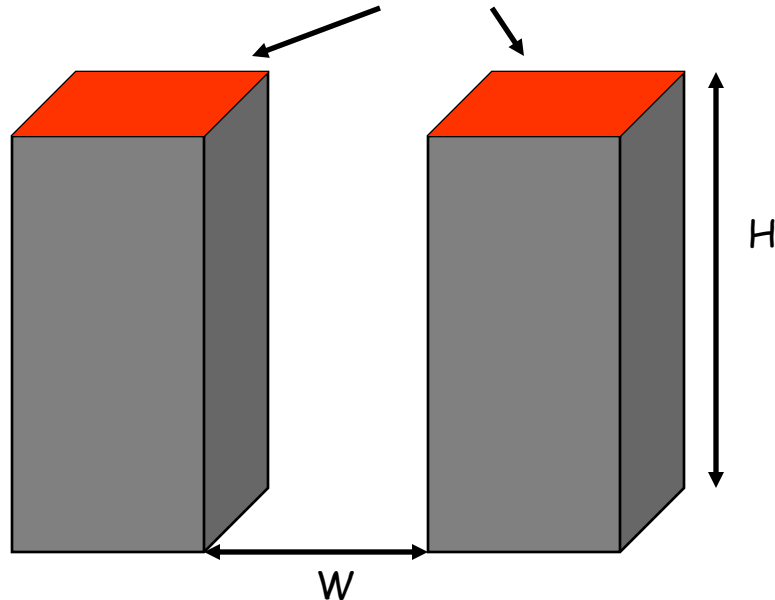


Roof area, W_{roof}



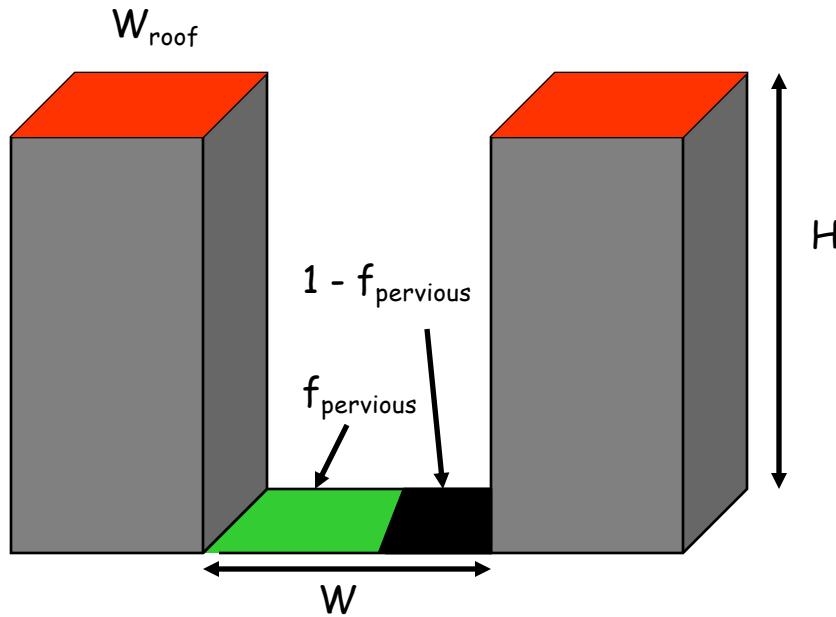
A substantial surface area is covered by roofs

Fraction of city covered by roofs, $0 \leq W_{\text{roof}} \leq 1$



$1 - W_{\text{roof}}$ is the fractional area of the urban canyon

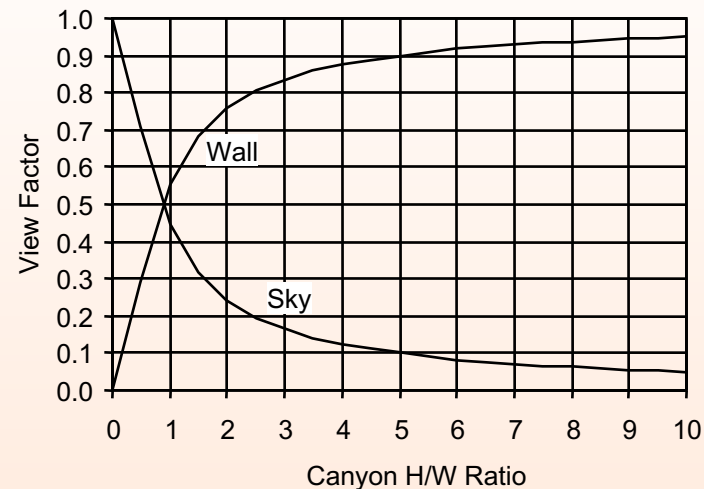
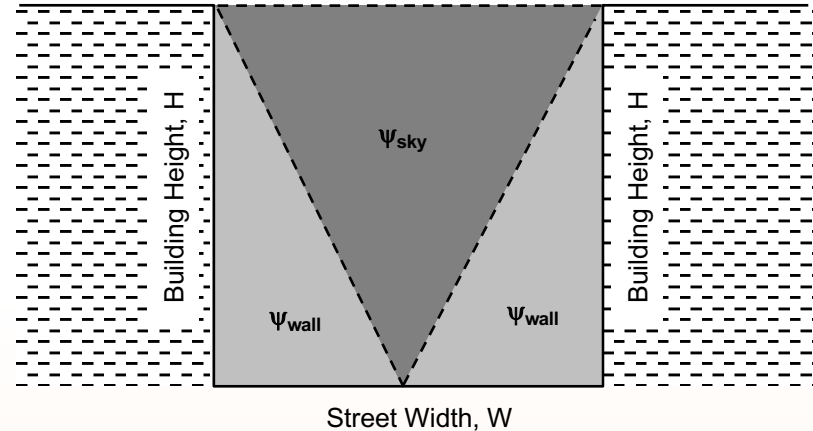
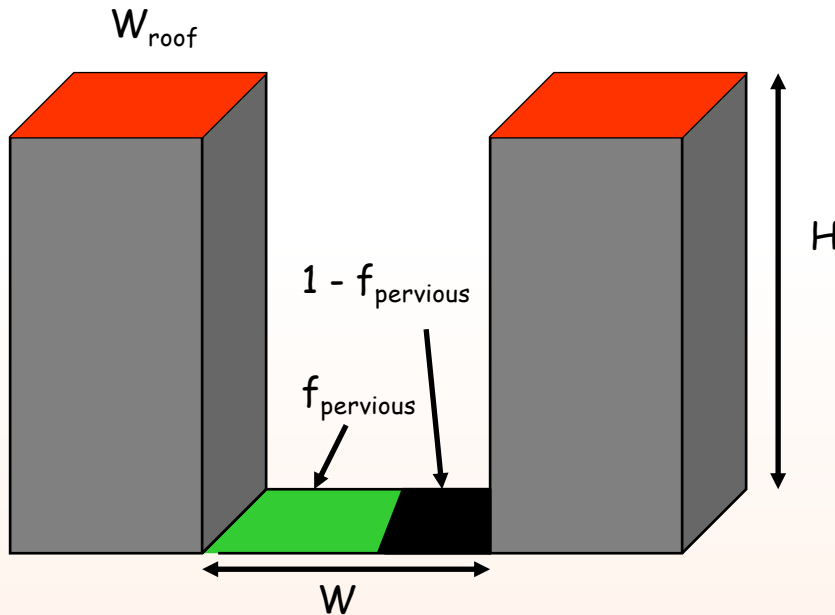
Urban parks, f_{pervious}



Impervious area = $1 - f_{\text{pervious}}$

Processes contributing to the UHI

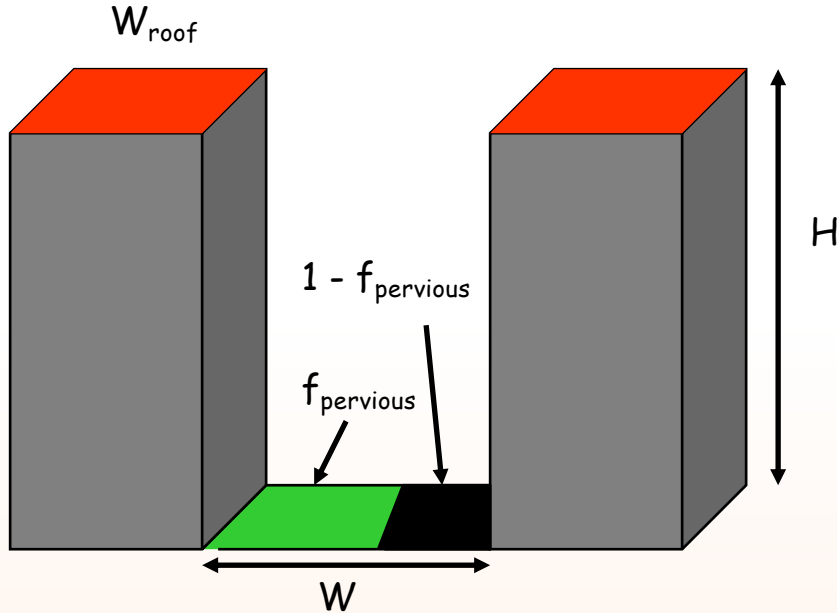
- Decreased surface longwave radiation loss due to reduction of sky view factor



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.

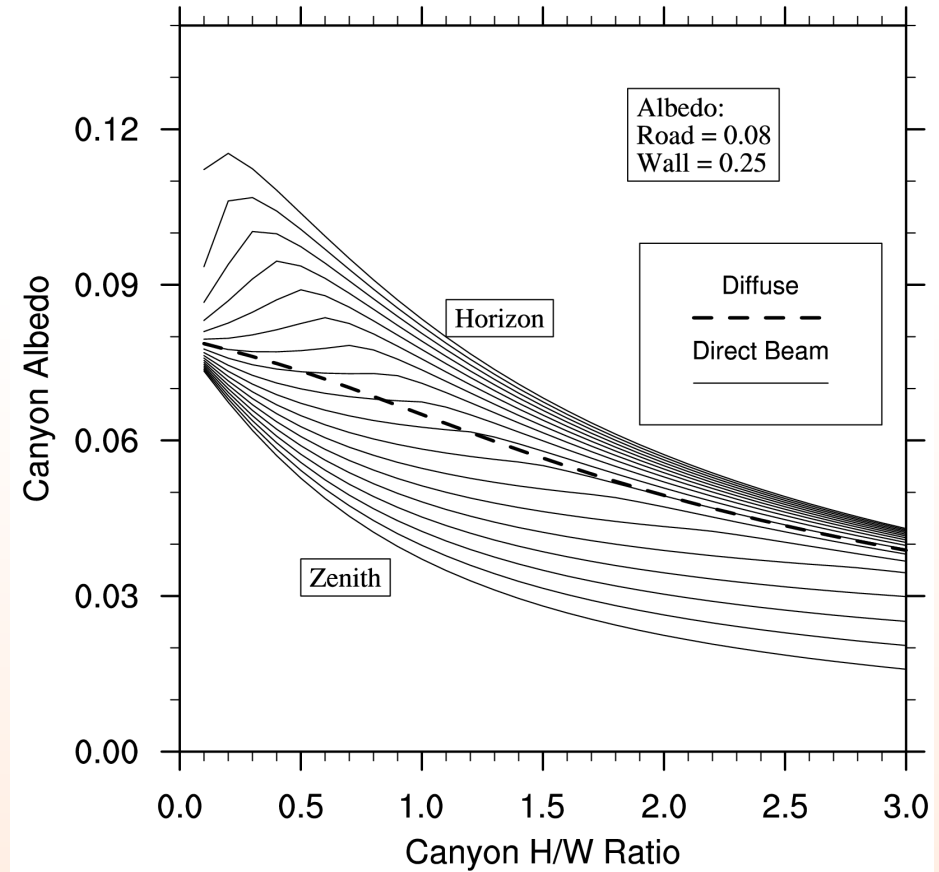
Processes contributing to the UHI

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



- 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.

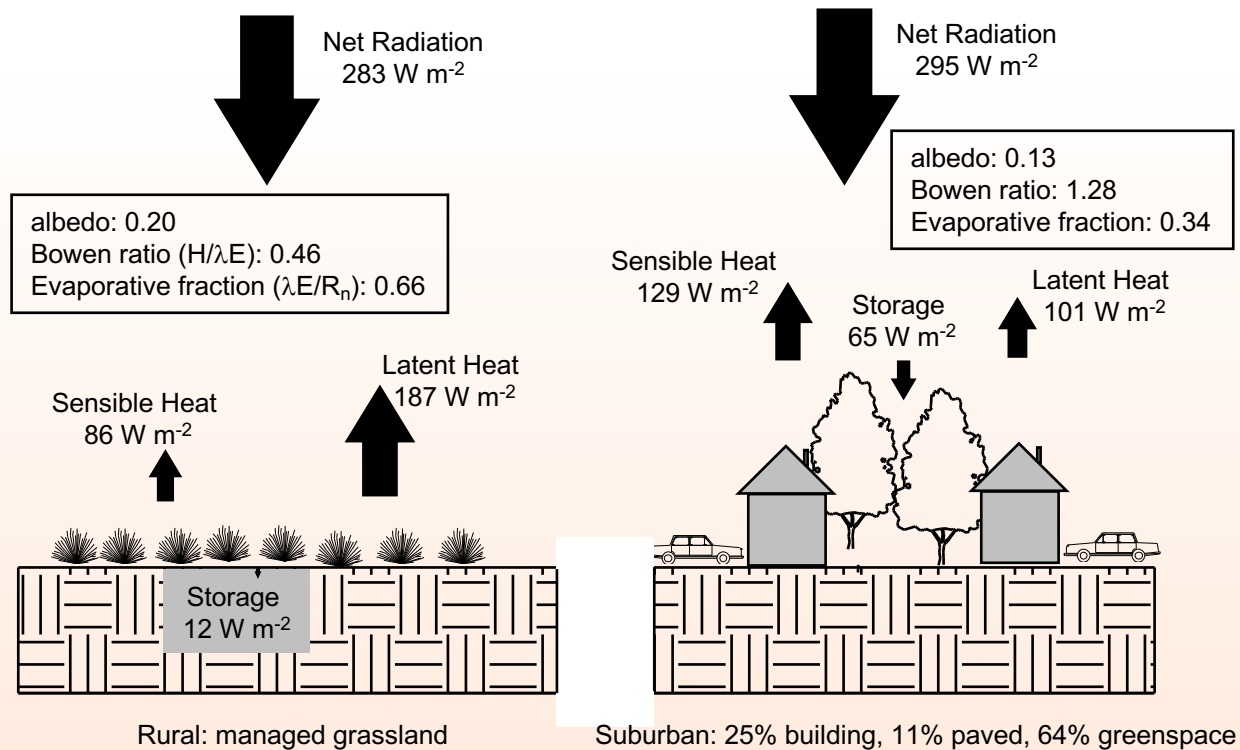


Oleson et al. (2008)

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

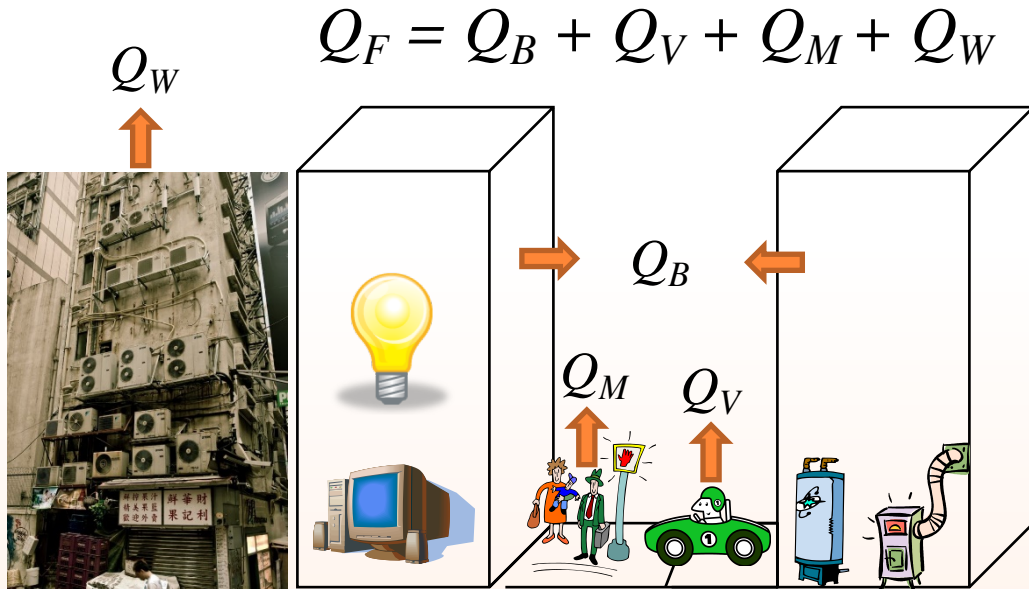
Surface energy fluxes, Vancouver, B.C.; average summer day



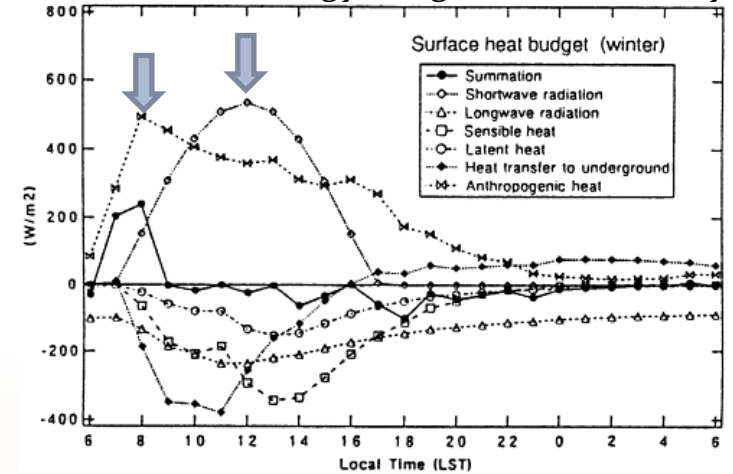
Cleugh & Oke (1986)

Processes contributing to the UHI

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

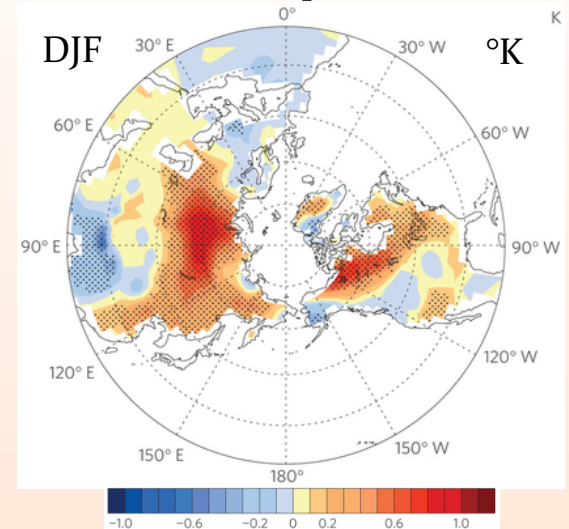


Winter surface energy budget in central Tokyo



Ichinose et al. (1999)

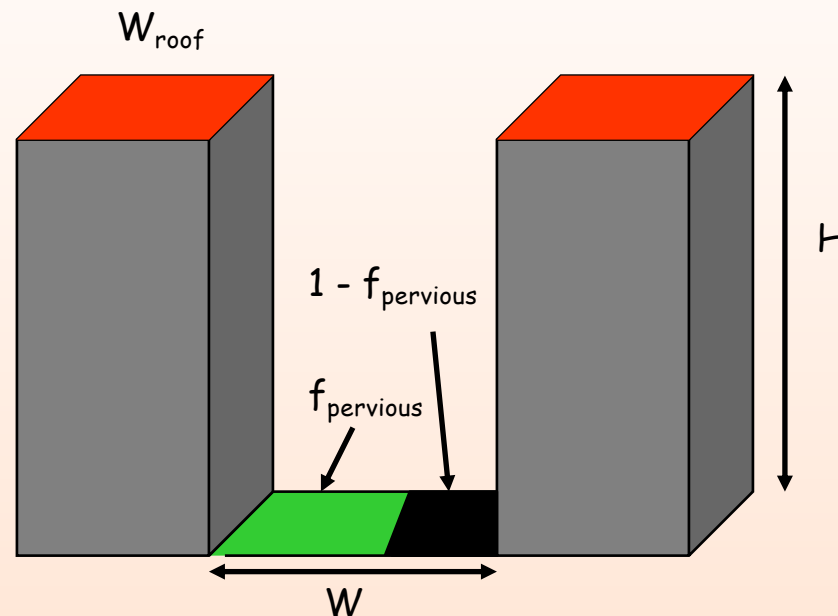
Mean surface air temperature difference



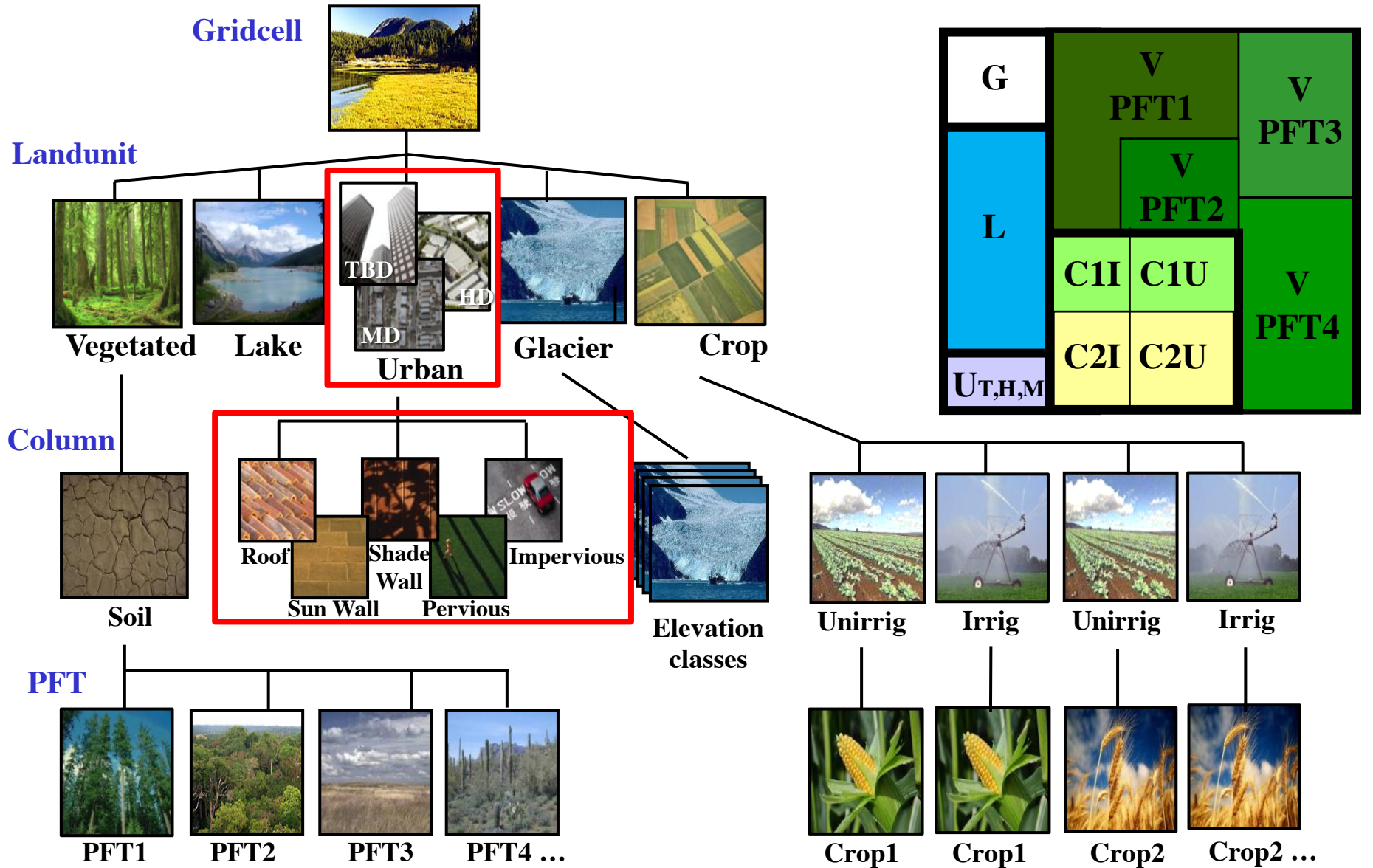
Zhang et al. (2013)

Processes contributing to the UHI

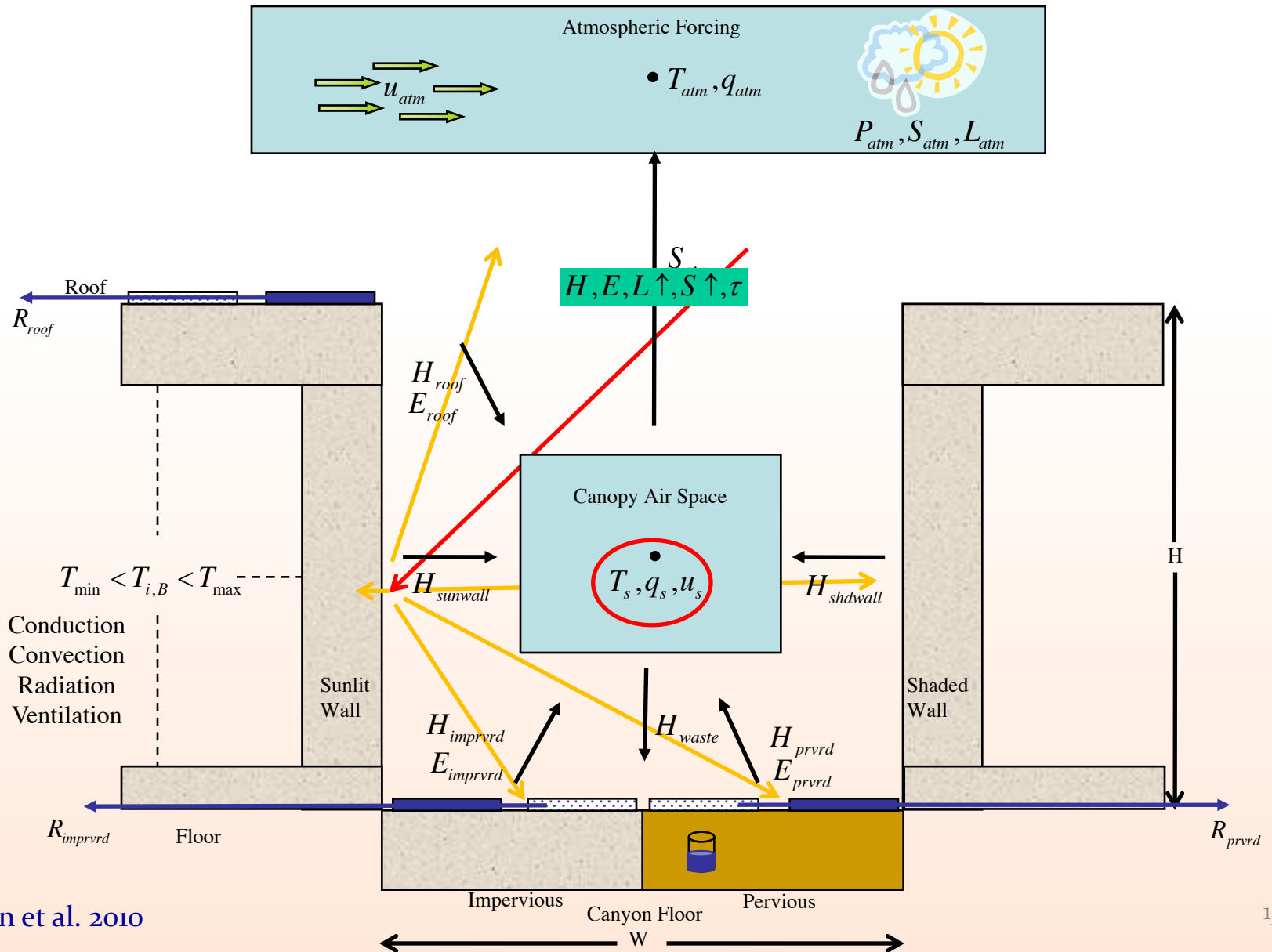
- Increased shortwave absorption due to trapping inside urban canyon (lower albedo)
- Decreased surface longwave radiation loss due to reduction of sky view factor
- Reduction of ET due to replacement of vegetation with impervious surfaces
- Increased storage of heat due to larger heat capacity of urban 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

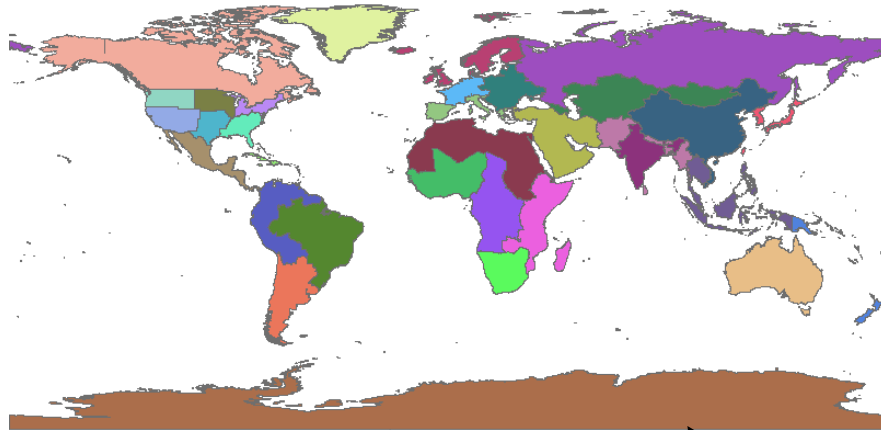


Community Land Model Urban



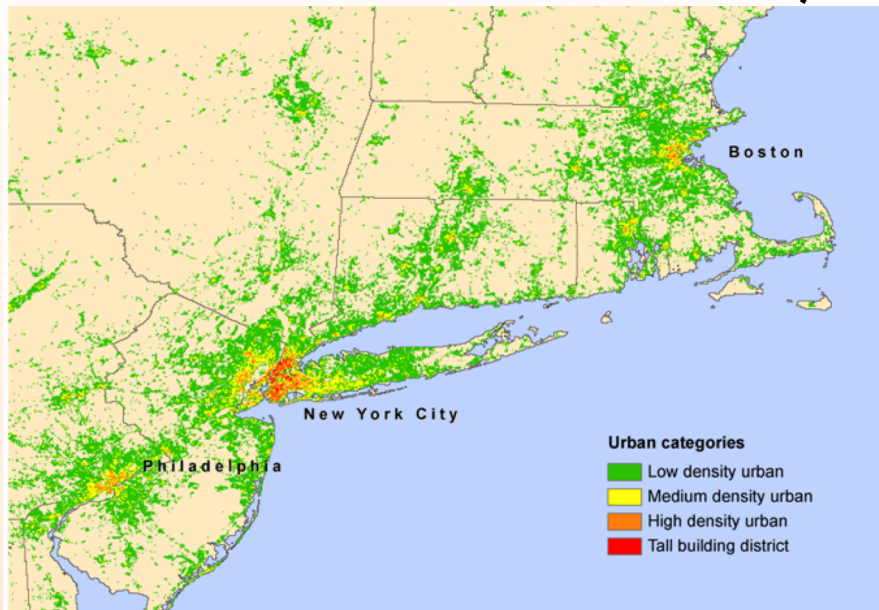
Global Urban Characteristics Dataset

Global Regions



→ To CLMU

Urban Extent - Landsat 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)¹⁶

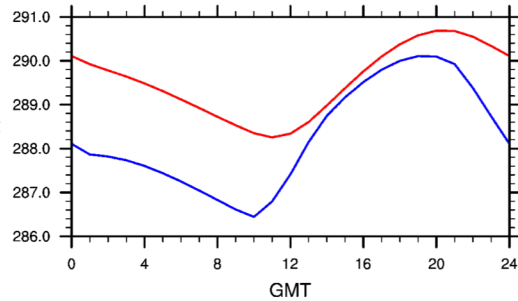
Jackson et al. 2010

Oleson and Feddema 2019, in review

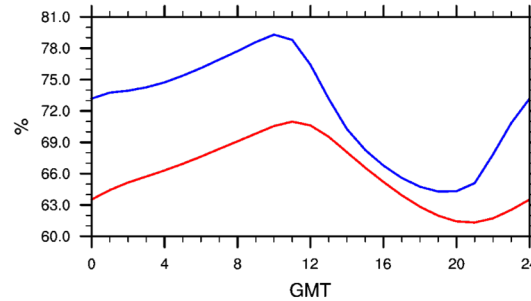
Modeled Urban and Rural Energy Balance

Annual Average Diurnal Cycle

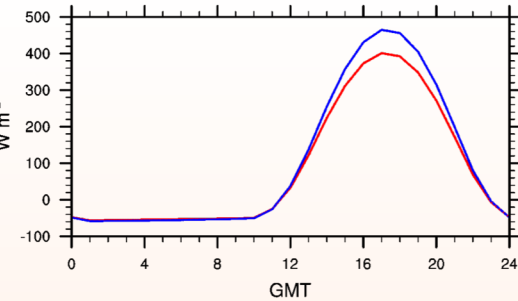
Air Temperature



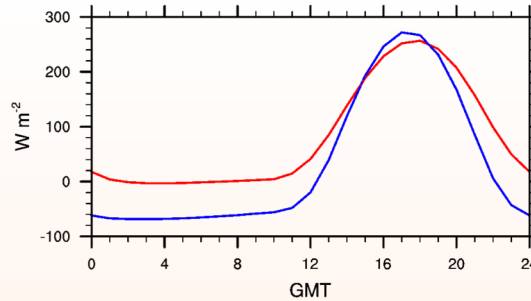
Relative Humidity



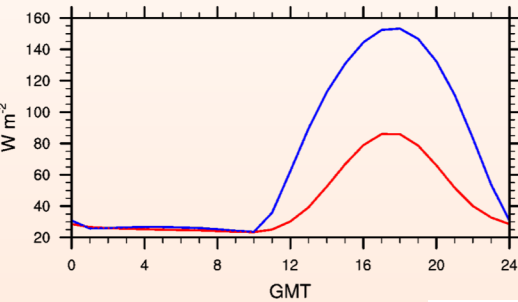
Net Radiation



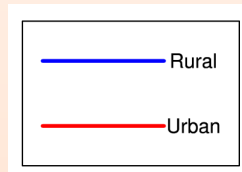
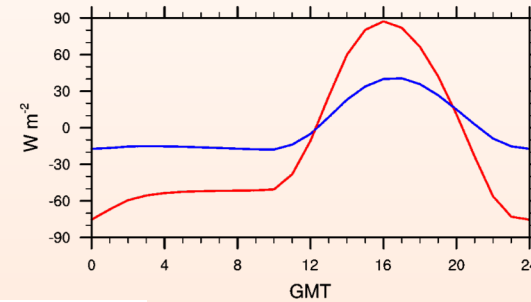
Sensible Heat



Latent Heat

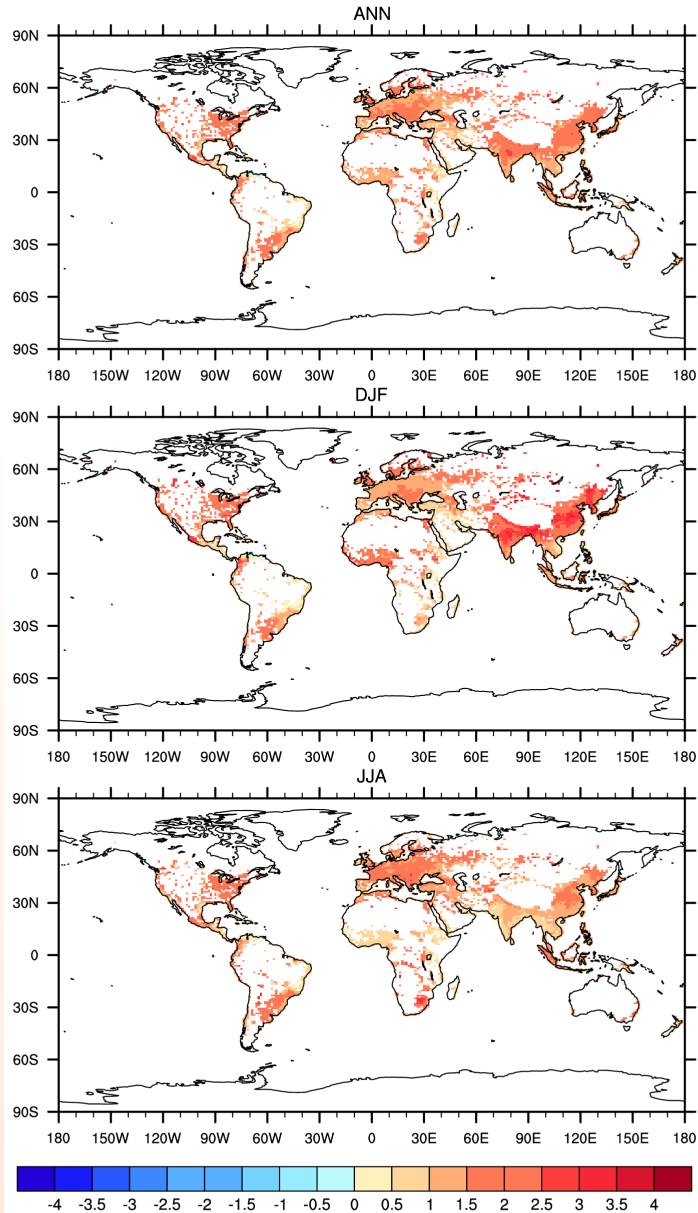


Storage



- 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

- Heat island positive almost everywhere, ranges from near-zero up to 4°C

DJF

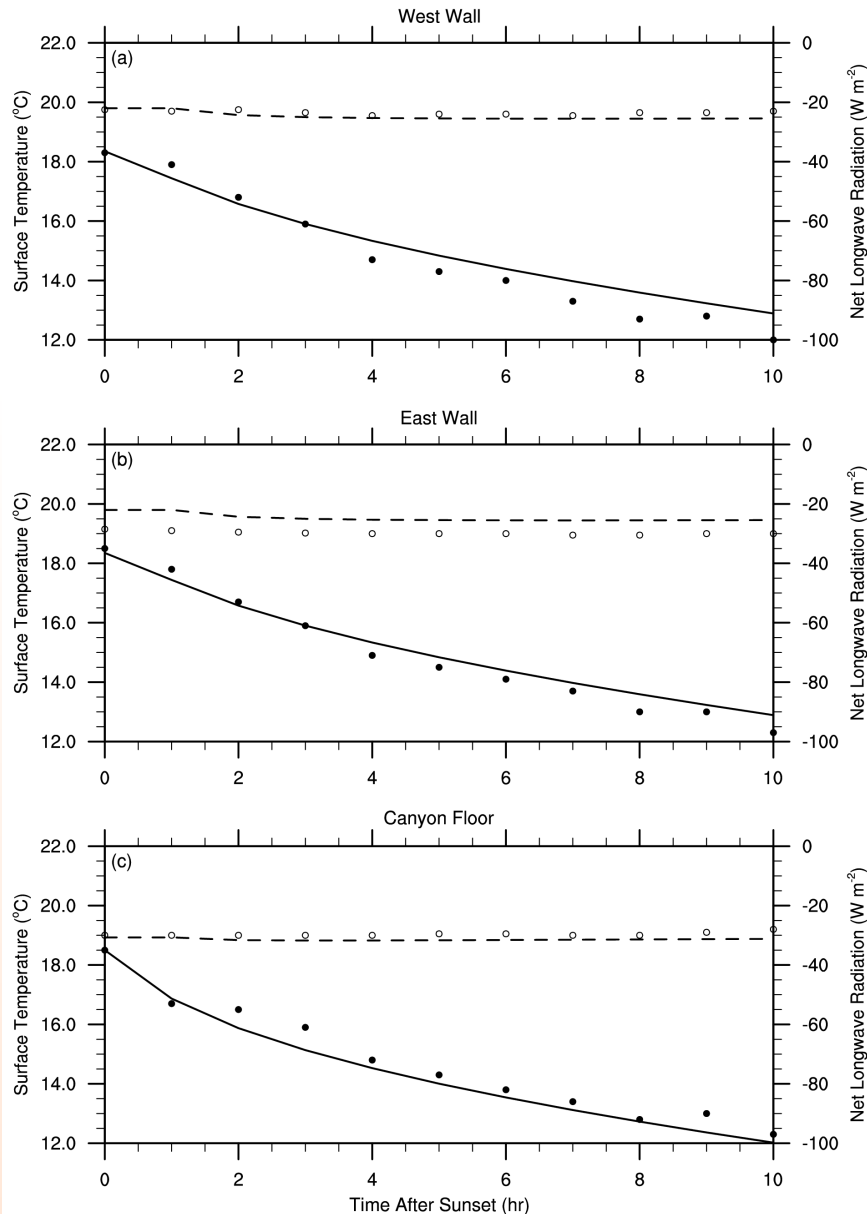
- Spatial/seasonal variability in the heat island caused by urban to rural contrasts in energy balance and response of these surfaces to seasonal cycle of climate

JJA

(°C)

Model Evaluation

Surface Temperature and Net Longwave Radiation



Simulated surface temperatures (solid lines) and net longwave radiation (dashed lines) compared to observations (circles) for A) west (east-facing) wall, B) east wall, and C) canyon floor for the night of September 9-10, 1973 in an urban canyon in the Grandview district of Vancouver, British Columbia (49°N, 123°W) (Nunez and Oke, 1976, 1977). Observed data from Figure 5 in Johnson et al. (1991).

Model Evaluation

Flux Towers

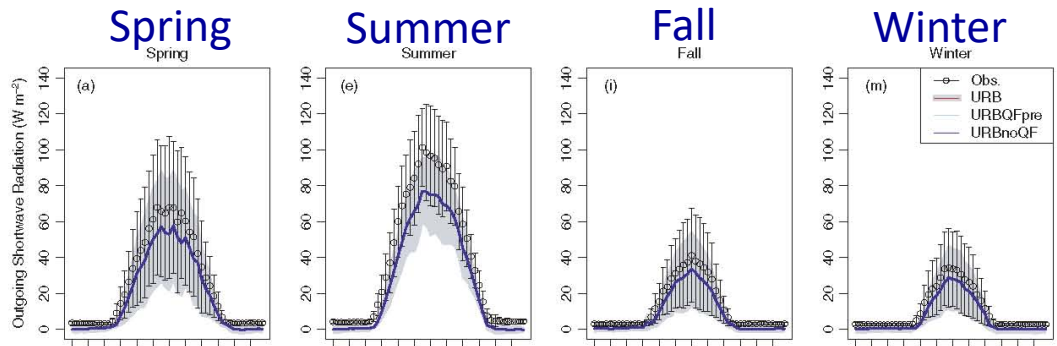


Source: Oke et al. 1999

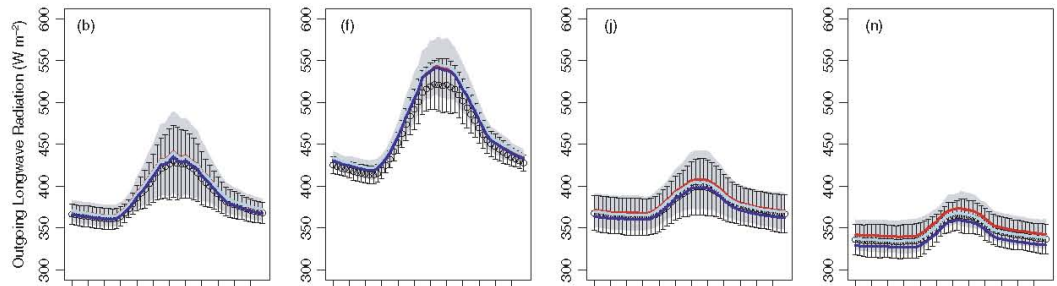
Fig. 2. The tower site at the School of Mines site in central Mexico City. The flux instruments (not visible) are mounted on the cross-arm at the top of the lattice section and just below the model owl (used to deter birds from perching on the sensors). Instruments were levelled; due to ground subsidence in this area the building top is not level. The shorter mast at the right was used for standard observations of temperature, humidity and wind.

Model Evaluation – Flux Tower Sites

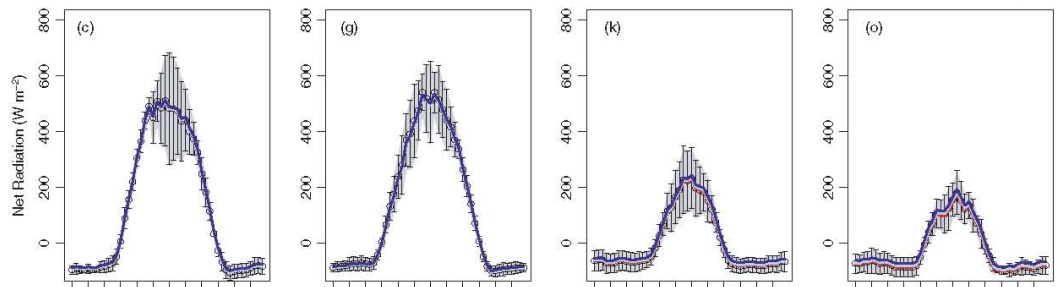
Outgoing shortwave radiation



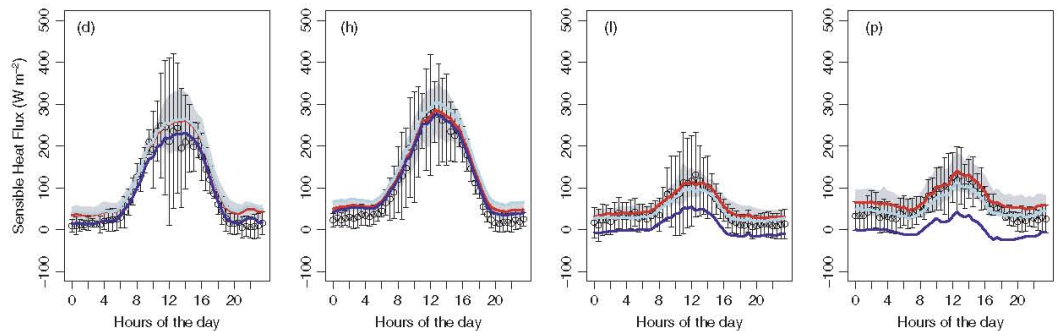
Outgoing longwave radiation



Net Radiation



Sensible Heat Flux



Toulouse
France
2004-2005
(Demuzere et al. 2013)

Urban Design to Mitigate the UHI and Climate Warming

- We can now model the temperature in cities and its response to climate change and we can explore strategies to mitigate the UHI and warming due to climate change.

Urban parks



Rooftop gardens



White roofs

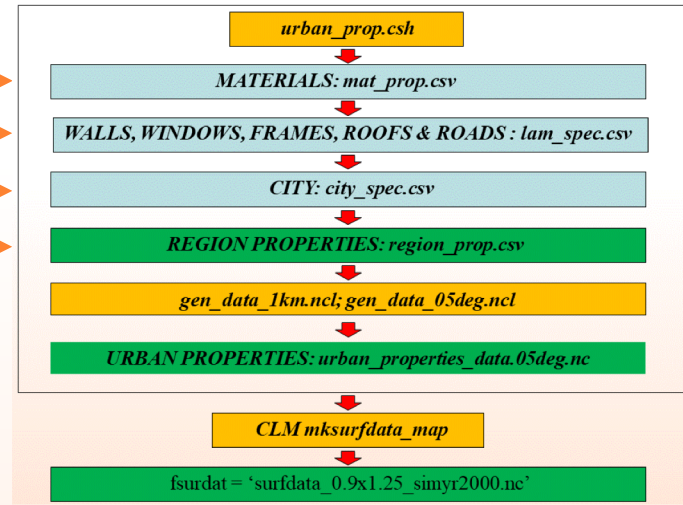


Green parking lots



Creating Scenarios – Urban Properties Tool

1. Outline overall scenario by region
2. Consider the need for new materials or modification of existing materials for all regions (e.g. duplicate a material but assign new albedo value) – change materials properties or add materials.
3. Modify wall/roof/road properties by substituting, adding or creating new types.
4. Assign wall and roof types to city types in a region
5. Alter city morphology parameters to represent building density and greenness

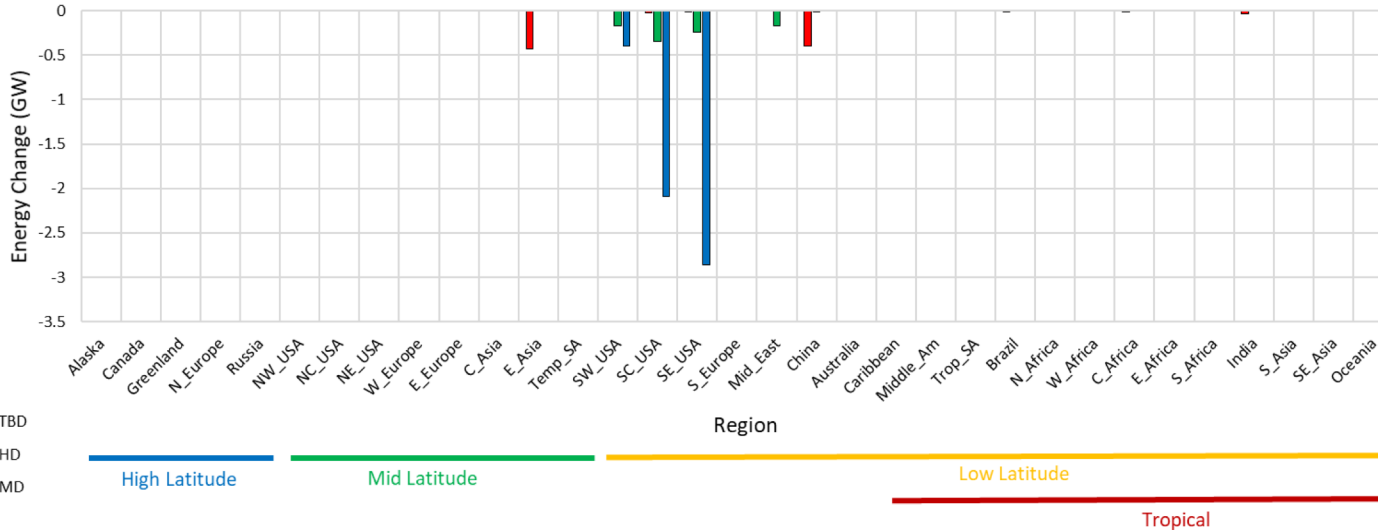


Scenario 6: Light Weight Insulated Walls and Roofs (LtWt)

- All walls are replaced by a lightweight (low heat capacity) wall made up of wood frames with cement particle board exteriors, extensive layers of insulation and dry wall interior walls.
- All roofs are made of EPDM, roof felt, 6 layers of insulation and two layers of interior drywall.
- Windows and window frames remain as presently specified. The walls and roofs have an albedo of 0.3 and emissivity of 0.9.
- Alterations:
 - lam_spec.csv
 - add light weight roof and wall laminates
 - city_spec.csv
 - Replace all walls and roofs globally

LtWt: annual energy change

ANN changes in AC (GW) for scenario CLM50_LtWt

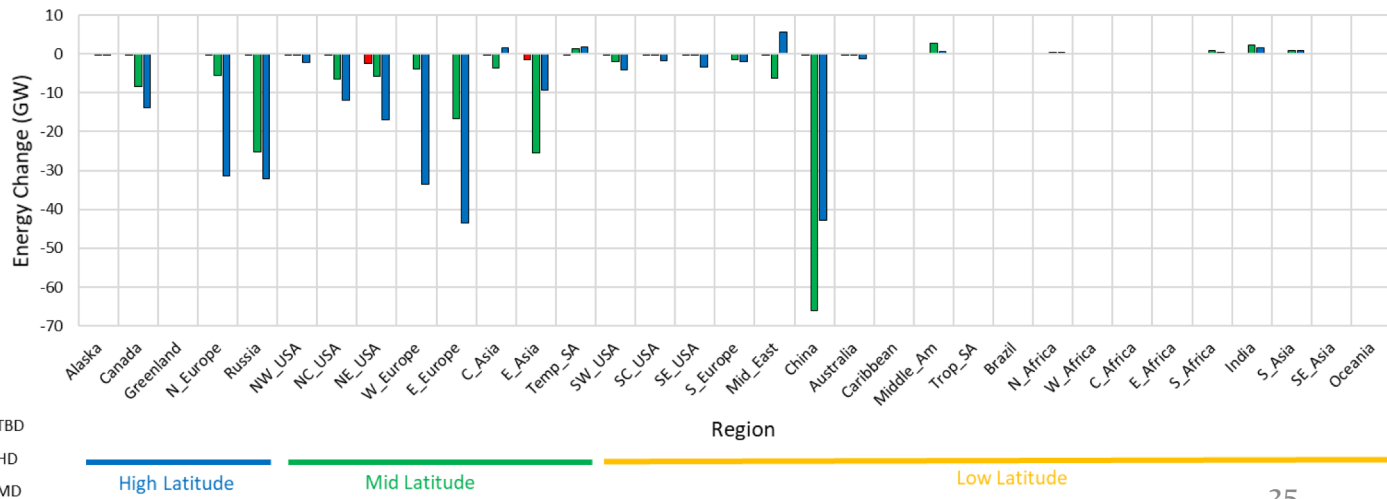


AC related energy use

Better insulation reduces AC where present and required

Heating related energy use

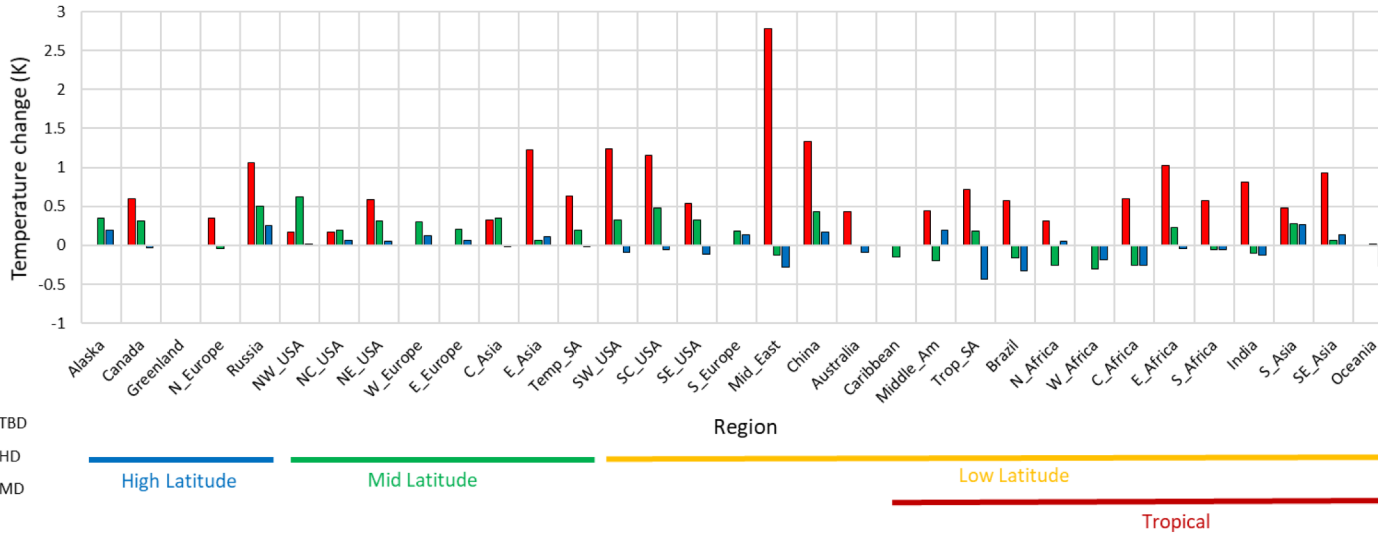
ANN changes in HEAT (GW) for scenario CLM50_LtWt



Better insulation reduces heating where required

LtWt: annual temperature change

ANN changes in TMAXU (K) for scenario CLM50_LtWt

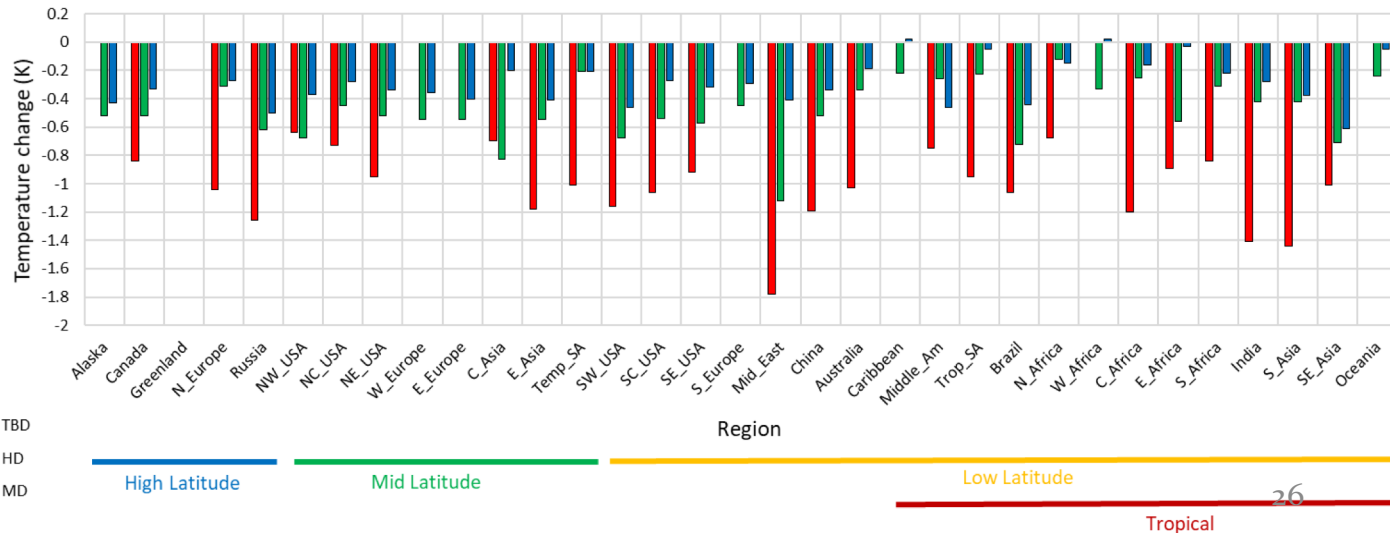


**T-max
change**

Less heat absorbed,
drives higher surface
and air temps

**T-min
change**

ANN changes in TMINU (K) for scenario CLM50_LtWt



Less stored heat
released at night
reduces temp

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
- Coarse 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 do not account for how urban areas 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
- 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.

Urban Modules

- `main/initGridCellsMod.F90`: initialize urban landunits
- `main/initVerticalMod.F90`: initialization for urban wall and roof layers and interfaces
- `main/clm_varcon.F90`: urban parameters
- `main/subgridAveMod.F90`: urban scaling to landunit/gridcell level
- `biogeophys/UrbanAlbedoMod.F90`: urban albedo
- `biogeophys/UrbanFluxesMod.F90`: urban turbulent/momentum fluxes, heat stress indices
- `biogeophys/UrbanParamsType.F90`: read in urban input data and namelist items, compute view factors and aerodynamic parameters
- `biogeophys/UrbanRadiationMod.F90`: urban radiation
- `biogeophys/UrbanTimeVarType.F90`: initialize and interpolate urban time-varying data (maximum interior building temperature)
- `biogeophys/UrbBuildTempOleson2015Mod.F90`: interior building temperature solution
- `biogeophys/SoilTemperatureMod.F90`: urban roof/wall/road temperatures
- `biogeophys/SoilFluxesMod.F90`: urban “ground heat” fluxes
- `biogeophys/SoilHydrologyMod.F90`, etc.: urban hydrology

CLMU Publications

- Oleson, K.W., and J. Feddema, 2019: Parameterization and surface data improvements and new capabilities for the Community Land Model Urban (CLMU), JAMES, in review.
- Jones, B., C. Tebaldi, B.C. O'Neill, K. Oleson, and J. Gao, 2018: Avoiding population exposure to heat-related extremes: demographic change vs climate change, *Climatic Change*, 146, 423-437, doi:10.1007/s10584-017-2133-7.
- Demuzere, M., S. Harshan, L. Jarvi, M. Roth, C.S.B. Grimmond, V. Masson, K.W. Oleson, E. Velasco, and H. Wouters, 2017: Impact of urban canopy models and external parameters on the modelled urban energy balance in a tropical city, *Quart. J. R. Meteor. Soc.*, doi:10.1002/qj.3028.
- Anderson, G.B., K.W. Oleson, B. Jones, and R.D. Peng, 2016: Classifying heatwaves: developing health-based models to predict high-mortality versus moderate United States heatwaves, *Climatic Change*, 146, 439-453, doi:10.1007/s10584-016-1776-0.
- Anderson, G.B., K.W. Oleson, B. Jones, and R.D. Peng, 2016: Projected trends in high-mortality heatwaves under different scenarios of climate, population, and adaptation in 82 US communities, *Climatic Change*, 146, 455-470, doi:10.1007/s10584-016-1779-x.
- Hu, A., S. Levis, G.A. Meehl, W. Han, W.M. Washington, K.W. Oleson, B.J. van Ruijven, M. He, and W.G. Strand, 2015: Impact of solar panels on global climate, *Nature Climate Change*, 6, 290-294, doi:10.1038/nclimate2843.
- Oleson, K.W., G.B. Anderson, B. Jones, S.A. McGinnis, and B. Sanderson, 2015: Avoided climate impacts of urban and rural heat and cold waves over the U.S. using large climate model ensembles for RCP8.5 and RCP4.5, *Climatic Change*, 146, 377-392, doi: 10.1007/s10584-015-1504-1.
- Karsisto, P., C. Fortelius, M. Demuzere, C.S.B. Grimmond, K.W. Oleson, R. Kouznetsov, V. Masson, and L. Jarvi, 2015: Seasonal surface urban energy balance and wintertime stability simulated using three land-surface models in the high-latitude city Helsinki, *Quart. J. R. Meteor. Soc. A*, 142, 401-417, doi:10.1002/qj.2659.
- Buzan, J.R., K. Oleson, and M. Huber, 2015: Implementation and comparison of a suite of heat stress metrics within the Community Land Model version 4.5, *Geosci. Model Dev.*, 8, 151-170, doi:10.5194/gmd-8-151-2015.
- Oleson, K.W., A. Monaghan, O. Wilhelmi, M. Barlage, N. Brunzell, J. Feddema, L. Hu, and D.F. Steinhoff, 2015: Interactions between urbanization, heat stress, and climate change, *Climatic Change*, 129, 525-541, DOI:10.1007/s10584-013-0936-8.

CLMU Publications

- Oleson, K.W., 2012: Contrasts between urban and rural climate in CCSM4 CMIP5 climate change scenarios, *J. Climate*, 25, 1390-1412, doi: 10.1175/JCLI-D-11-00098.1.
- Demuzere, M., K.W. Oleson, A.M. Coutts, G. Pigeon, and N.P.M. Van Lipzig, 2013: Simulating the surface energy balance over two contrasting urban environments using the Community Land Model Urban (CLMU), *Int. J. Clim.*, DOI:10.1002/joc.3656.
- Fischer, E.M., K.W. Oleson, and D.M. Lawrence, 2012: Contrasting urban and rural heat stress responses to climate change, *Geophys. Res. Lett.*, 39, L03705, DOI:10.1029/2011GL050576.
- Grimmond, C.S.B., et al., 2011: Initial results from phase 2 of the international urban energy balance model comparison, *Int. J. Clim.*, 31, 244-272, doi:10.1002/joc.2227.
- Oleson, K.W., G.B. Bonan, J. Feddema, and T. Jackson, 2011: An examination of urban heat island characteristics in a global climate model, *Int. J. Clim.*, 31, 1848-1865, DOI:10.1002/joc.2201.
- Oleson, K.W., G.B. Bonan, and J. Feddema, 2010: The effects of white roofs on urban temperature in a global climate model, *Geophys. Res. Lett.*, 37, L03701, doi:10.1029/2009GL042194.
- Jackson, T.L., J.J. Feddema, K.W. Oleson, G.B. Bonan, and J.T. Bauer, 2010: Parameterization of urban characteristics for global climate modeling, *A. Assoc. Am. Geog.*, 100:4, 848-865, doi:10.1080/00045608.2010.497328.
- Grimmond, C.S.B., et al., 2010: The International Urban Energy Balance Models Comparison Project: first results from phase I, *J. Appl. Meteorol. Clim.*, 49, 1268-1292, doi: 10.1175/2010JAMC2354.1.
- Oleson, K.W., G.B. Bonan, J. Feddema, M. Vertenstein, and C.S.B. Grimmond, 2008a: An urban parameterization for a global climate model. 1. Formulation and evaluation for two cities, *J. Appl. Meteorol. Clim.*, 47, 1038-1060.
- Oleson, K.W., G.B. Bonan, J. Feddema, and M. Vertenstein, 2008b: An urban parameterization for a global climate model. 2. Sensitivity to input parameters and the simulated urban heat island in offline simulations, *J. Appl. Meteorol. Clim.*, 47, 1061-1076.
- Oleson, K.W., G.B. Bonan, J.J. Feddema, M. Vertenstein, and E. Kluzek, 2010: Technical description of an urban parameterization for the Community Land Model (CLMU), NCAR Technical Note NCAR/TN-480+STR, 169 pp.

Thank You!

Questions?



Urban Heat Island Mitigation - White Roofs

Mesoscale modeling studies indicate that city-scale increases in albedo lead to cooler daytime air temperatures (0.5-2°C (Sailor 1995; Taha et al. 1999; Synnefa et al. 2008 [roofs only])).

What is the role of roofs in the urban energy budget, their contribution to the urban heat island, and the effectiveness of white roofs as a UHI mitigation technique ?

CON – control w/default urban parameter

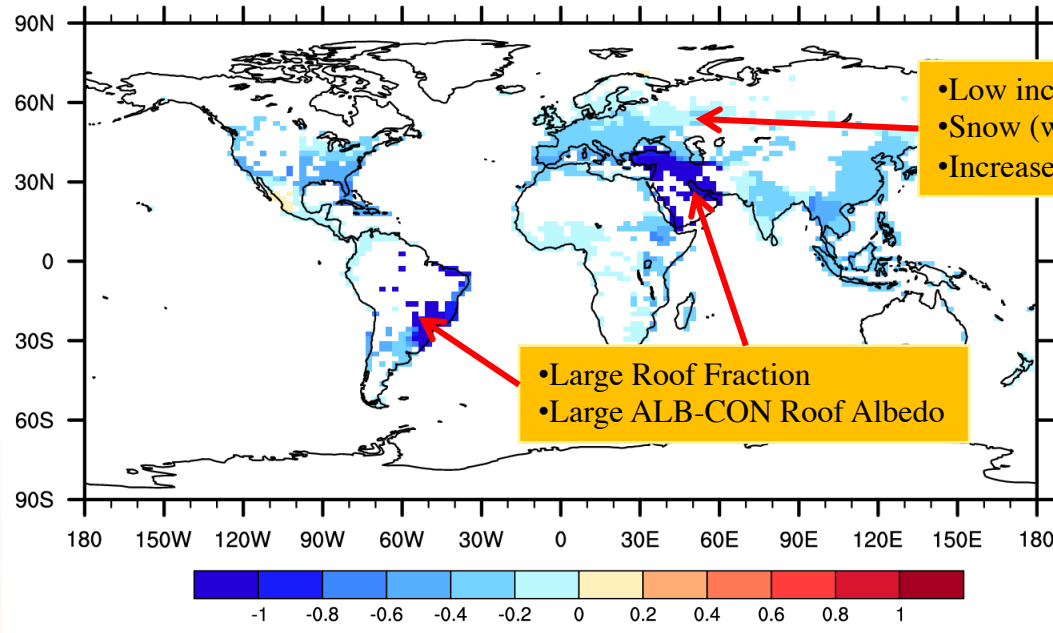
ALB - prescribe global white roof albedo of 0.9.

Oleson et al. 2010, *Geophys. Res. Lett.*



Urban Heat Island Mitigation - White Roofs

Reduction in the annual mean Heat Island (°C)



Increasing global roof albedo to 0.9 in CLMU reduces annual UHI by 1/3 on average.

Effectiveness of white roofs as a UHI mitigation technique varies according to urban design properties, climate, and interactions with space heating.

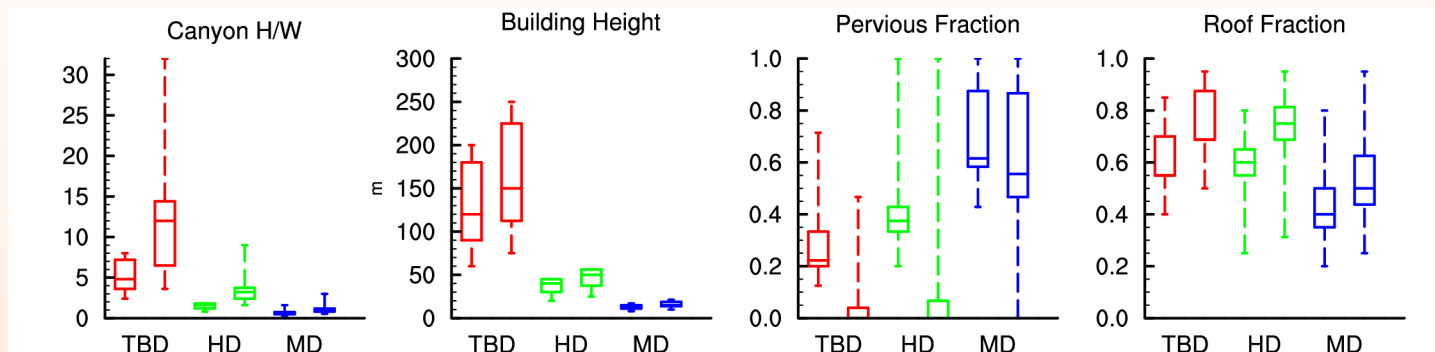
How will urban areas change in the future?

Increase urban density to accommodate growth in urban dwellers and population

To represent an increase in urban density, we arbitrarily increase roof (building) fraction by 25% for all density types and assume this is preferentially accommodated by a decrease in the fraction of pervious canyon floor. Building height is increased by 25%.

Changes in Global Urban Properties

Morphological – Urban Density



We expect that this will **increase the UHI** because, e.g., there will be more solar and longwave radiation trapping with larger H/W and less latent heat flux because of a reduction in pervious surface.

Global Offline CLM4.5SP Simulations

CONTROL: Control simulation is run from 1850-2100 using 20th century and Representative Concentration Pathway 8.5 (RCP8.5) atmospheric forcing from CESM MOAR. Base case building stock.

DENSITY: increase in urban density (RCP8.5 2081-2100)

DENSITY+3P WINDOWS: DENSITY + triple-pane windows

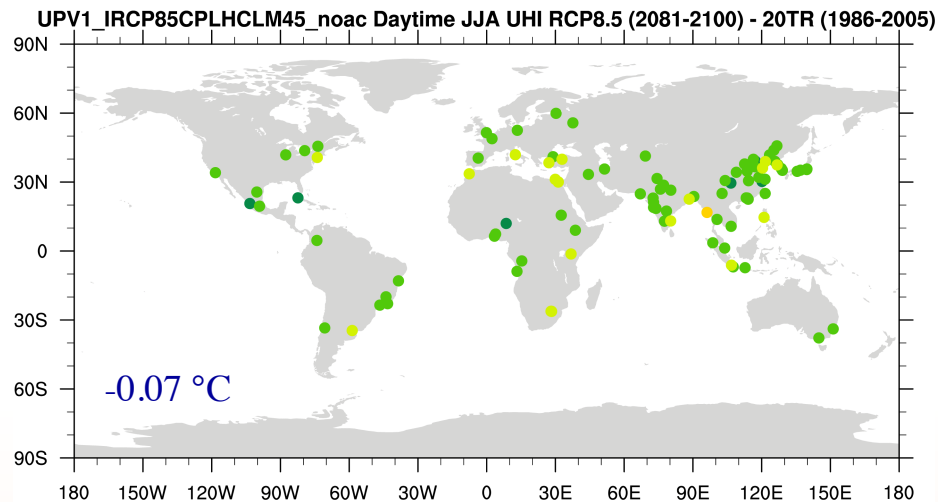
What are the effects on the UHI?

100 most populous world settlements (GRUMP v1)

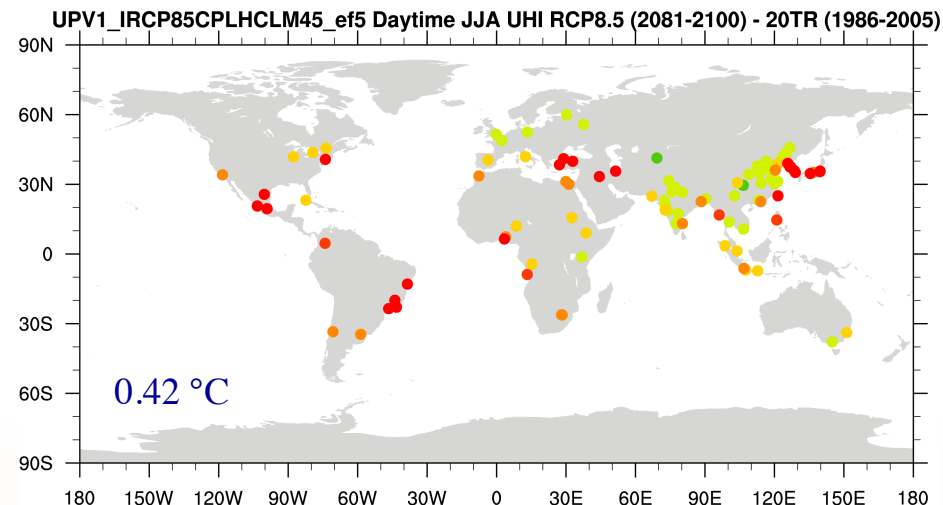
Changes in JJA Daytime Urban Heat Island: (2081-2100) – (1986-2005)

PD: 0.73 °C

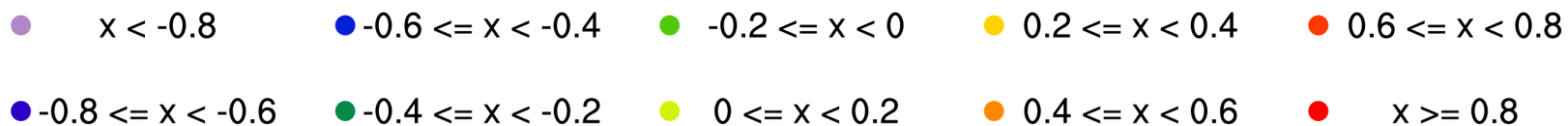
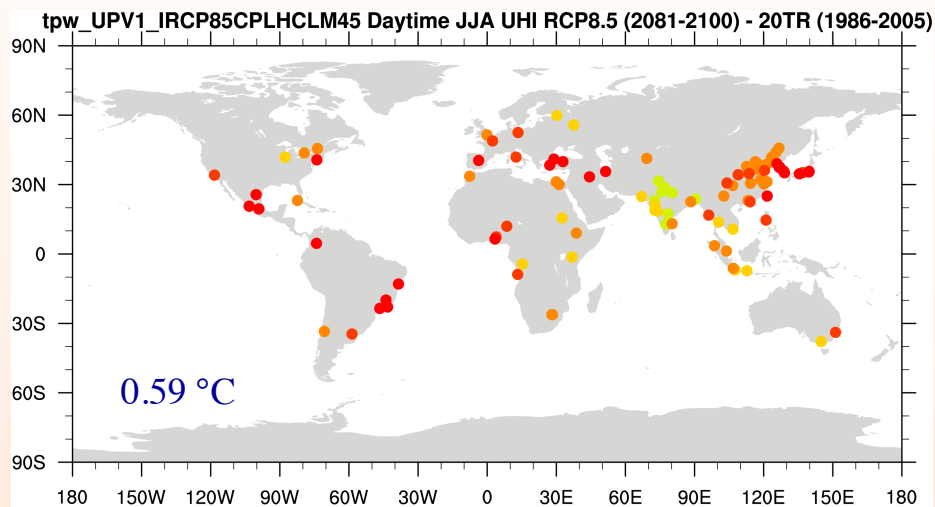
CONTROL



DENSITY



DENSITY + 3P WINDOWS

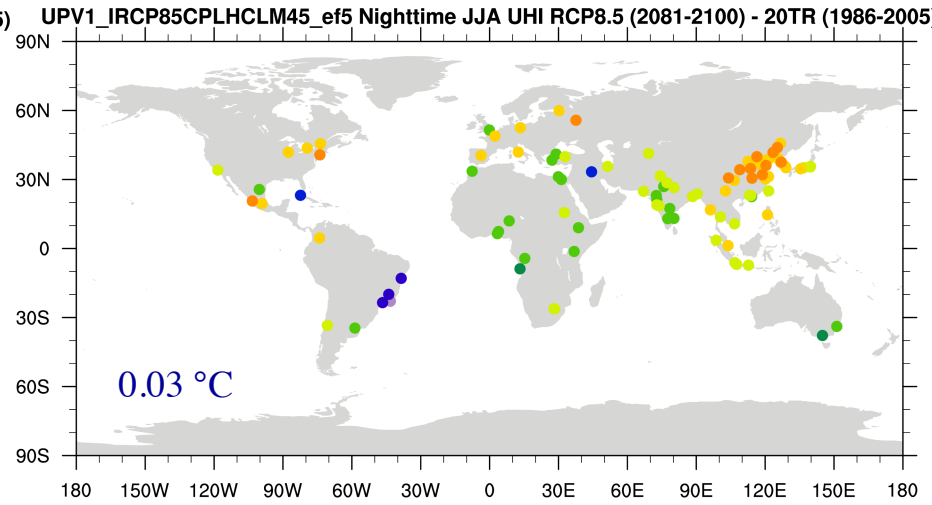
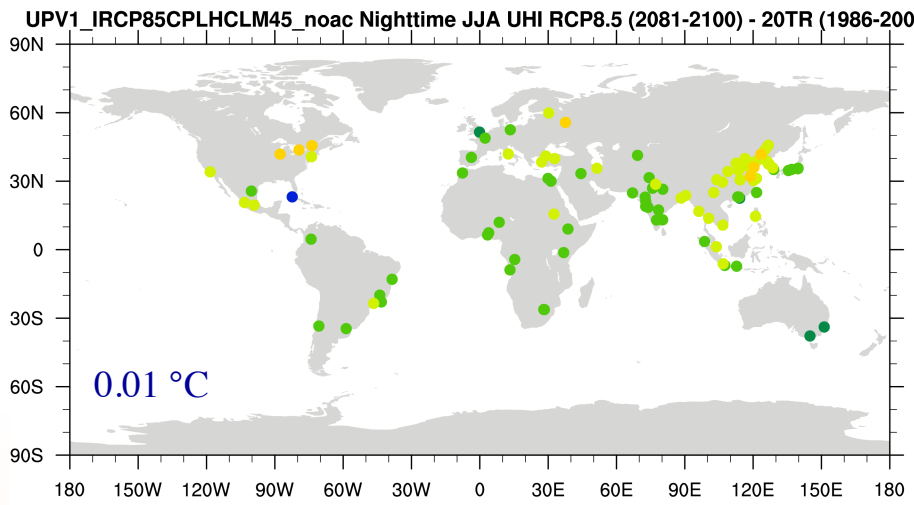


Changes in JJA Nighttime Urban Heat Island: (2081-2100) – (1986-2005)

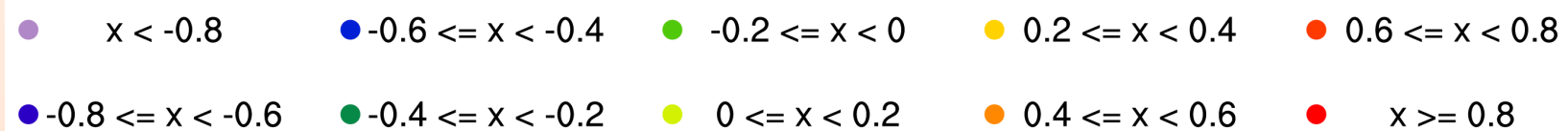
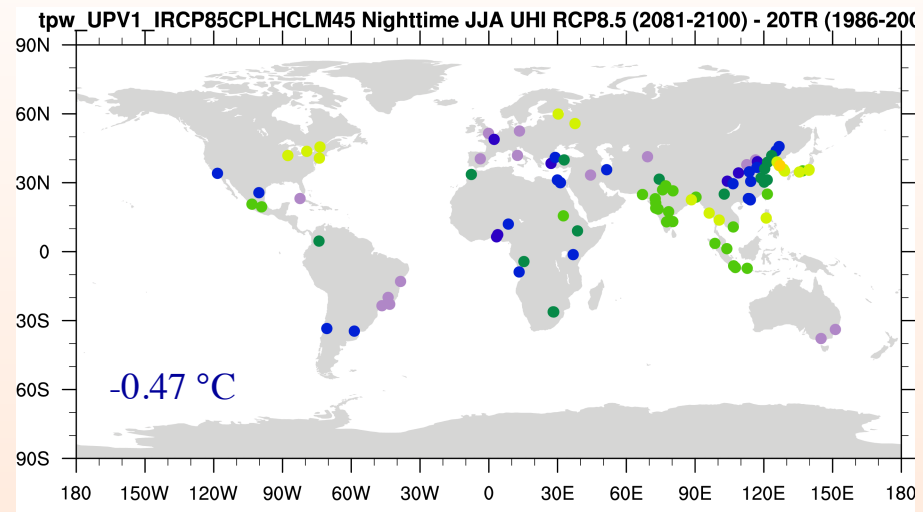
PD: 1.26 °C

CONTROL

DENSITY

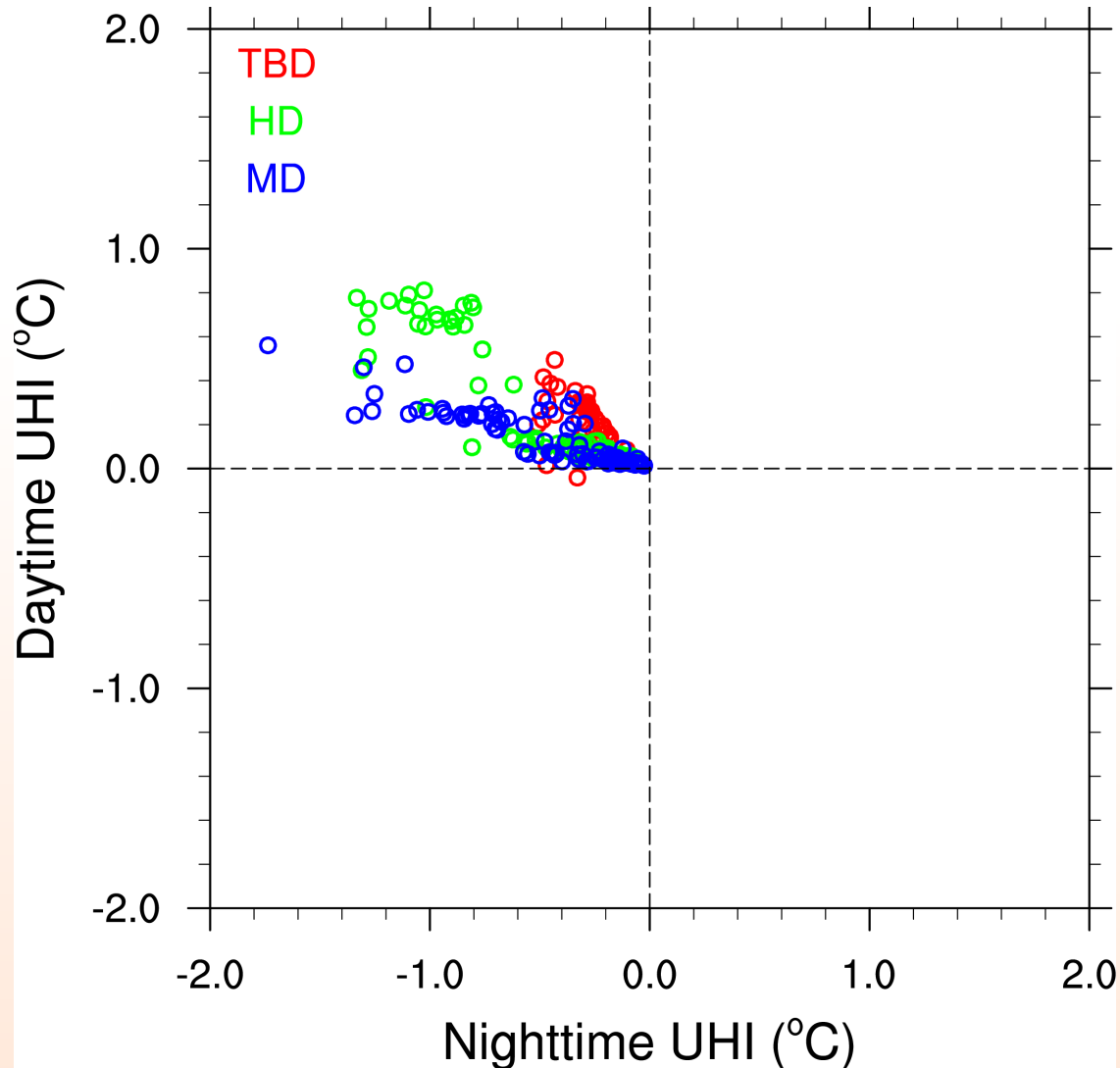


DENSITY + 3P WINDOWS



**Changes in JJA Daytime and Nighttime UHI by density class: (2081-2100)
100 most populous settlements (GRUMP v1)**

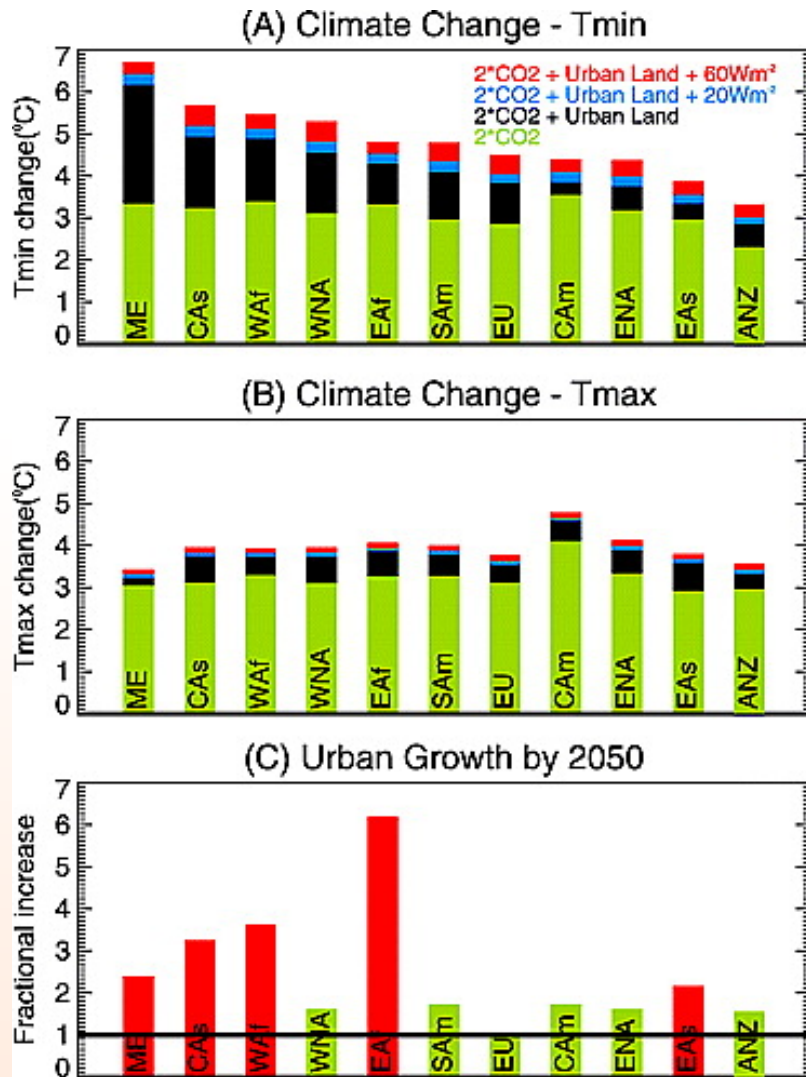
(DENSITY+3P WINDOWS) - DENSITY



Summary

- ❑ An increase in global urban living space (through an increase in density) of 50% at 2081-2100 results in increases of 57% and 7% in daytime and nighttime global average UHI compared to present day, respectively.
- ❑ Conversion to triple pane windows further increase the daytime UHI by 23%. The increase in nighttime UHI due to density is more than offset and is reduced by 37% compared to present day.
- ❑ Results vary spatially/temporally and depend on the same factors that determine the heat island in the first place (urban properties, mix of density types, rural landcover, and climate).

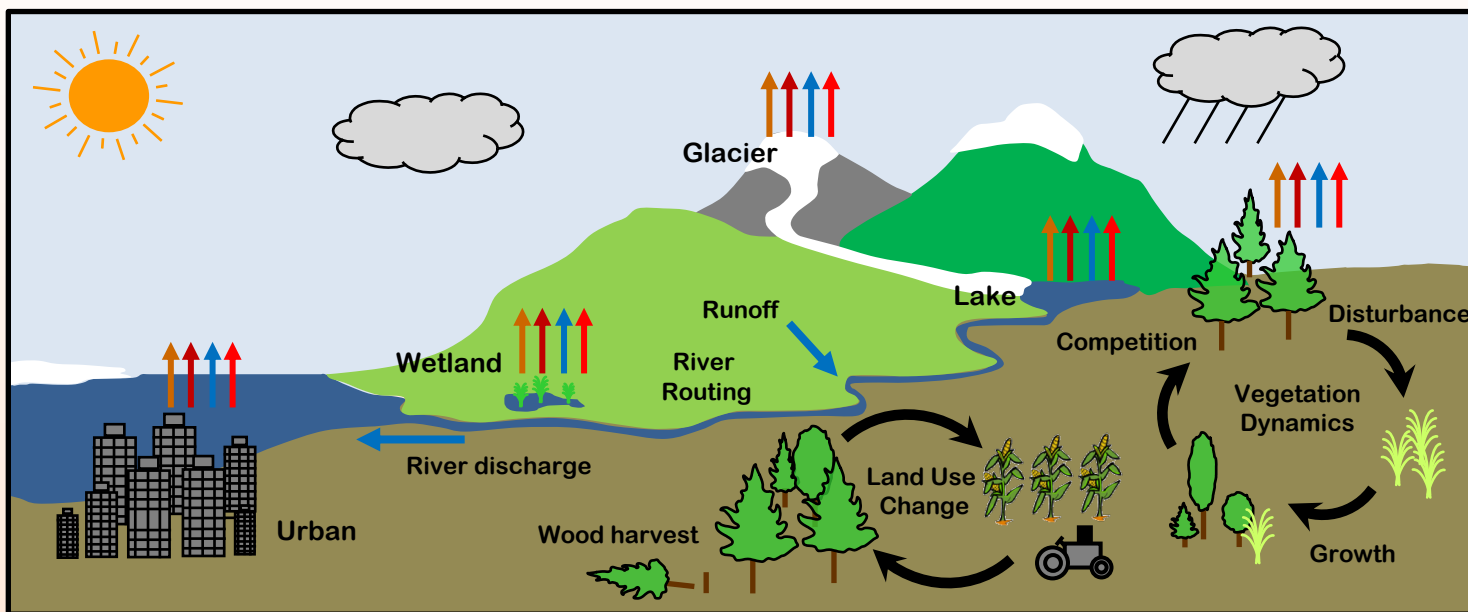
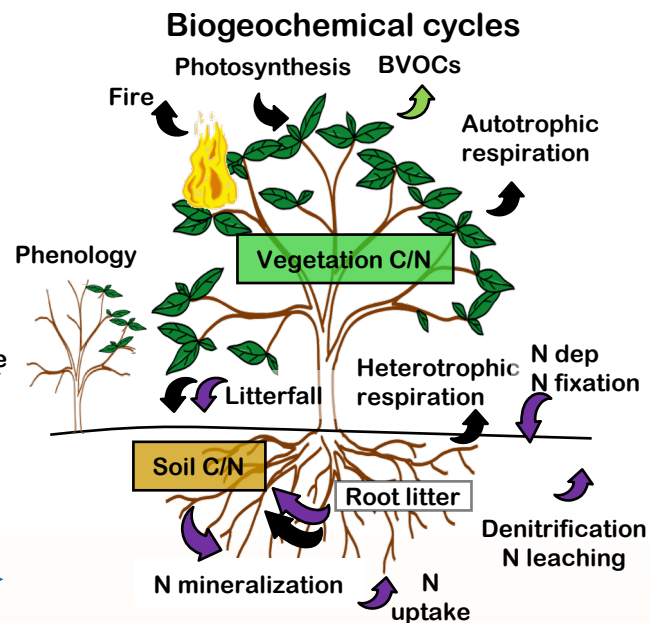
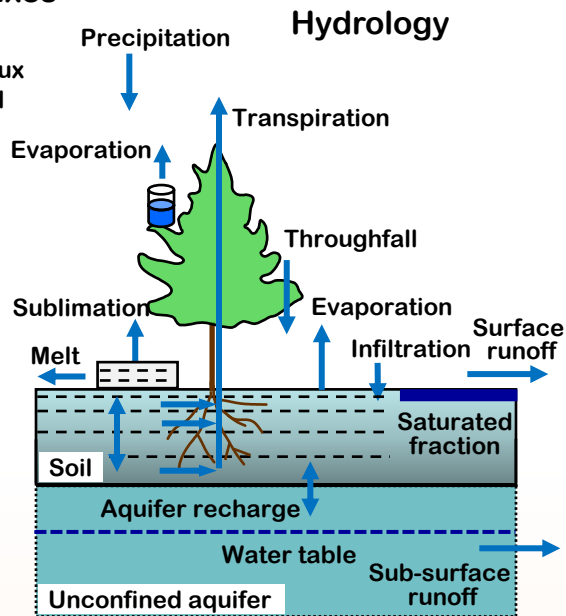
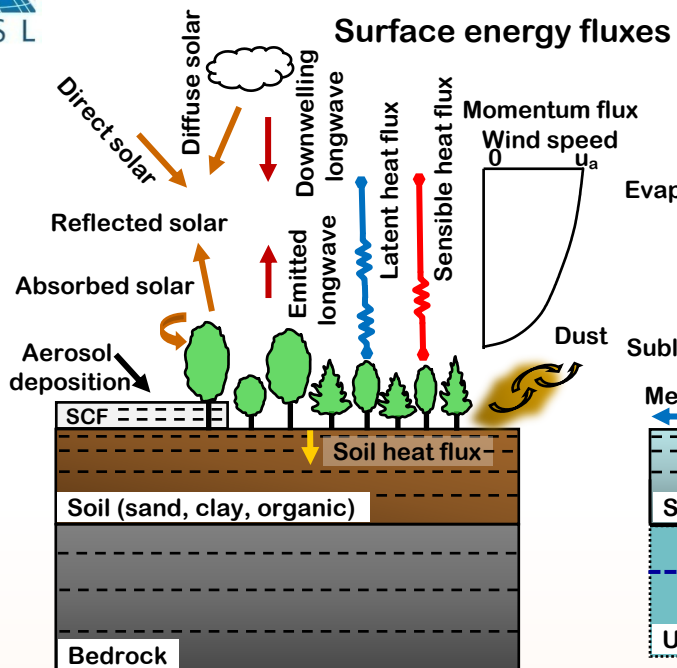
Why represent urban areas in a climate model?



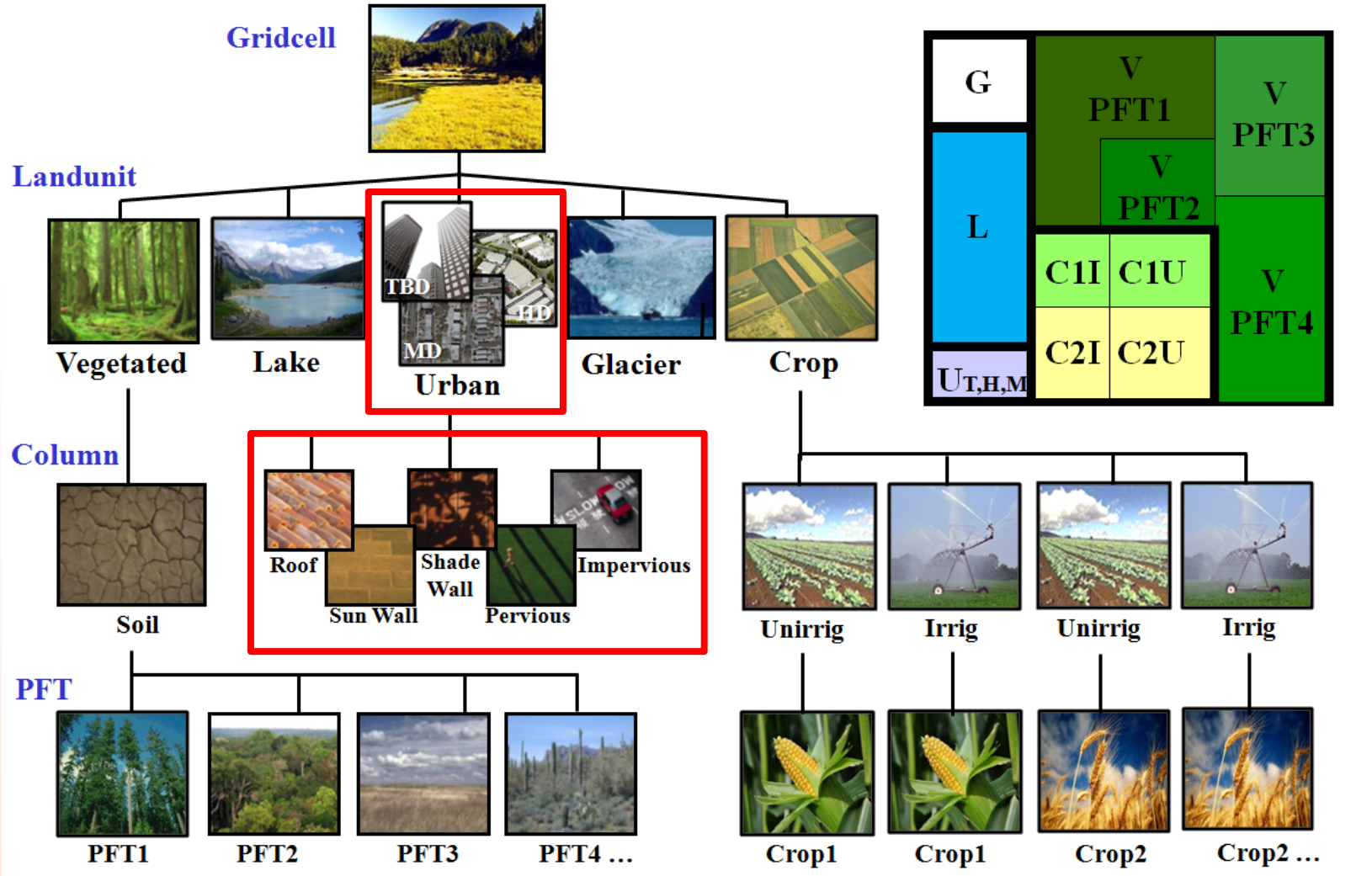
McCarthy et al. 2010

- The majority of the world's population now lives in urban areas. This is where they feel the effects of climate change. Until recently, global climate change simulations have failed to account for urban areas.
- “Those regions with the higher cumulative impact of climate change and urban effects are...also projected to at least double their urban populations by 2050” (McCarthy et al. 2010)
- It is important to consider the additional urban warmth as well as how climate change and urban areas might interact.

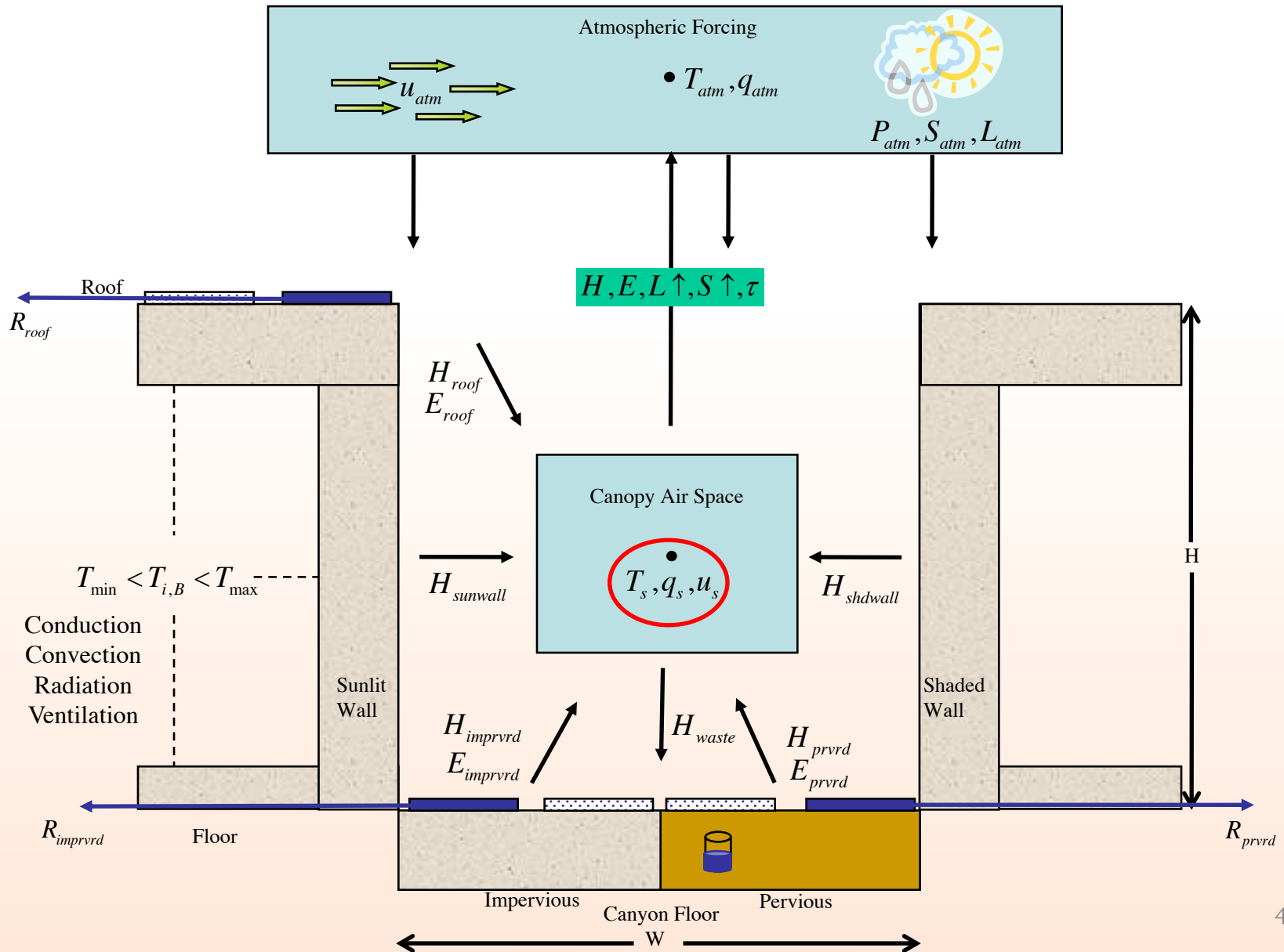
Community Land Model (CLM)



Incorporating Urban Areas into CLM



Community Land Model Urban

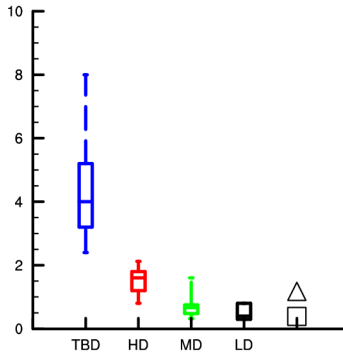


Urban properties

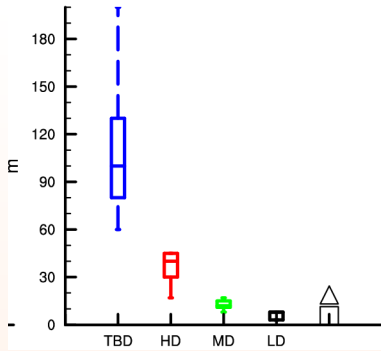
Tall Building District

Global

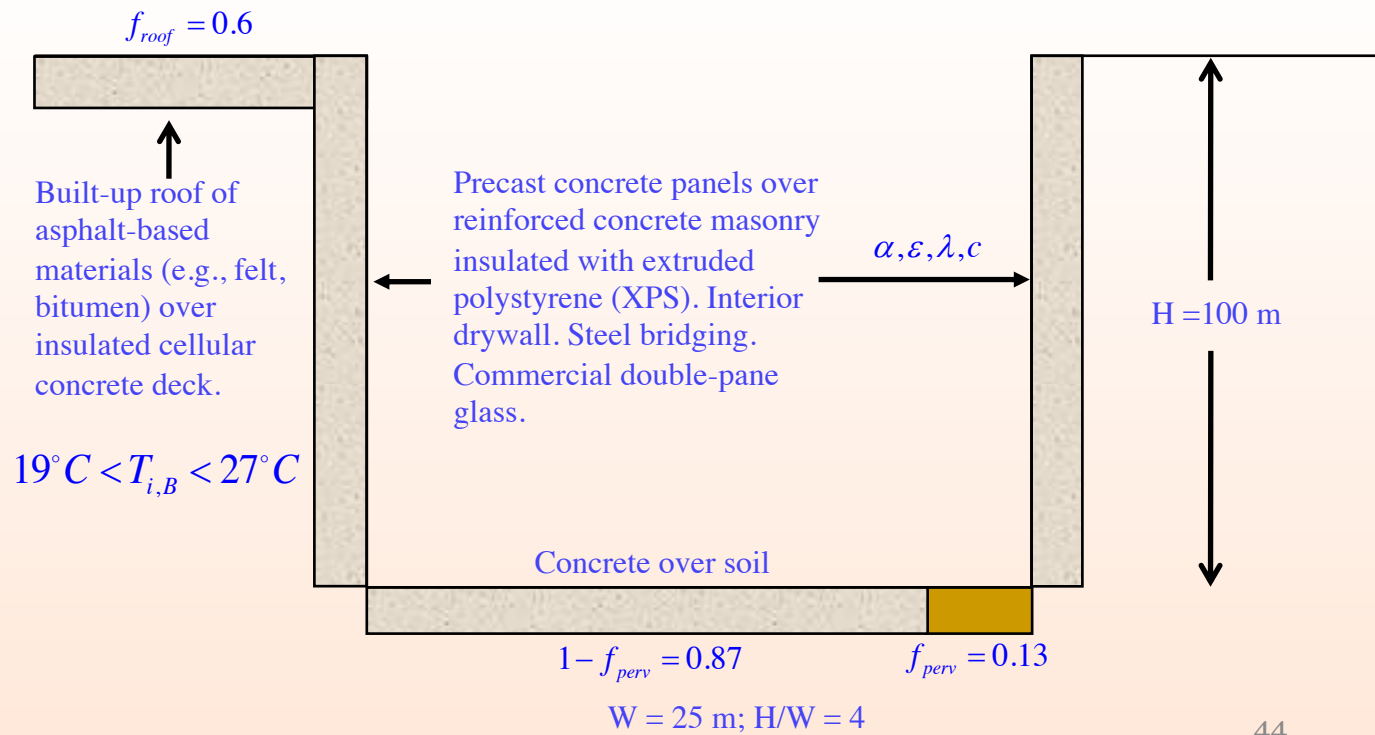
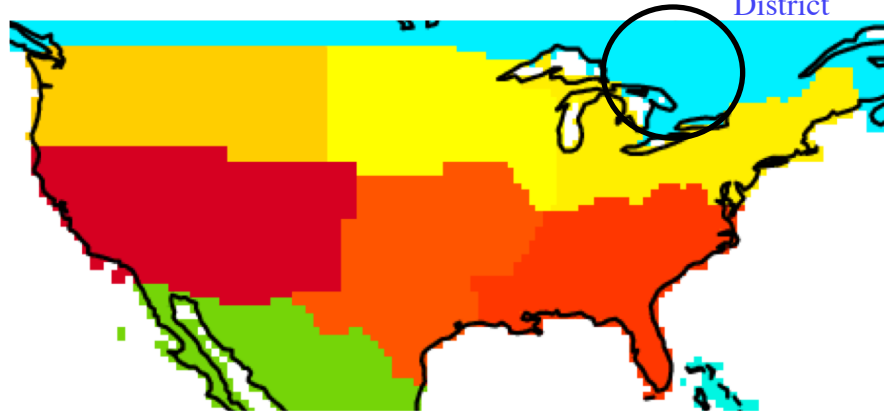
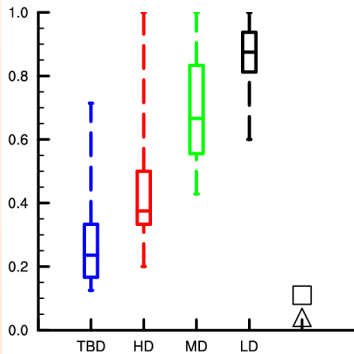
Canyon H/W



Building Height



Pervious Fraction



Urban Density Classes

Urban Class	H/W	Building Heights (m)	Pervious Fraction (%)	Population Density (km ²)	Typical Building Types
Tall Building District (TBD)	4.6	40-200+	5-15	14,000 - 134,000+	Skyscrapers
High Density (HD) Residential/ Commerical/ Industrial	1.6	17-45	15-30	5,000 - 80,000+	Tall apartments, office bldgs, industry
Medium Density (MD) Residential	0.7	8-17	20-60	1,000 - 7,000	1-3 story apartment bldgs, row houses

Model Evaluation

Global observations suitable for evaluating the urban model are simply unavailable. Therefore, strategy is to develop confidence in the model through a mix of quantitative and qualitative studies at smaller scales:

- Several of CLMU parameterizations and numerical schemes are taken from CLM when urban and vegetation/soil/snow treatments are expected to be similar (e.g., heat transfer), and CLM is a well-tested model.
- Process-level studies – e.g., evaluation of canyon albedo
- Performance against flux tower measurements
- Performance against other models
- Does CLMU capture typical observed characteristics of urban climates (e.g., heat islands) in a qualitative sense?

Model Evaluation

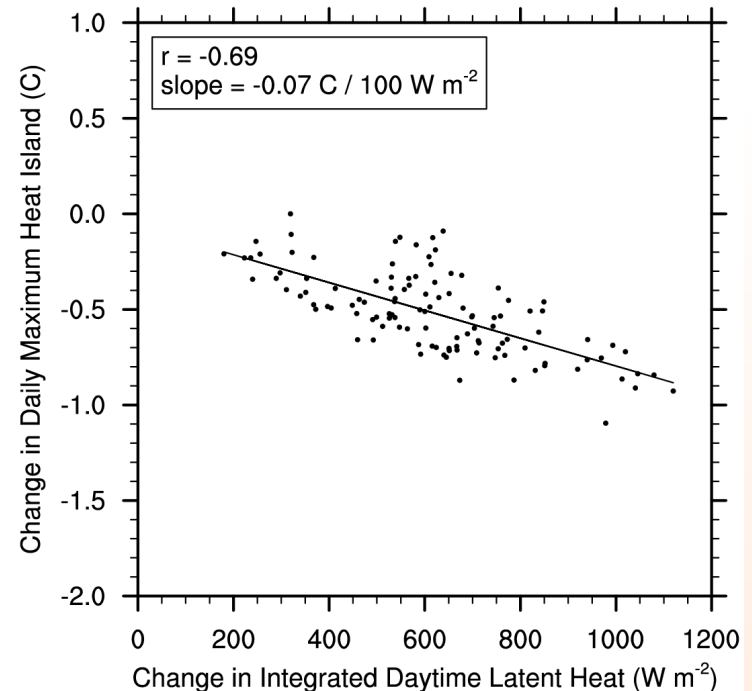
Reduction of ET due to replacement of vegetation with impervious surfaces (or as shown here, addition of pervious surface decreases the heat island)

Simulations over the U.S. with:

$$H/W = 3 \quad \text{vs.} \quad H/W = 3$$

$$f_{\text{pervious}} = 0.8 \quad f_{\text{pervious}} = 0$$

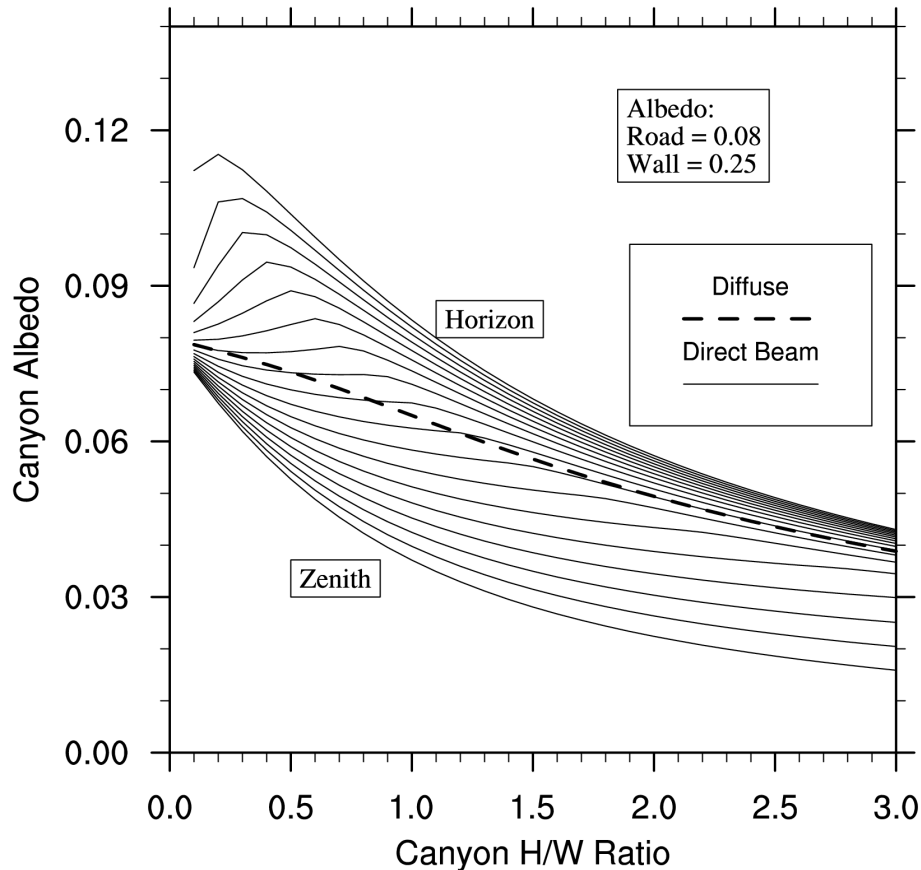
- The urban heat island is smaller overall with the pervious surface, decreasing in proportional to increasing latent heat flux
- Variability in response due in part to moisture availability



Change in daily average maximum heat island in summer as a function of summed hourly daytime latent heat flux

Model Evaluation

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



- 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.

Direct beam and diffuse albedo of the urban canyon (walls and road) as a function of height to width ratio.

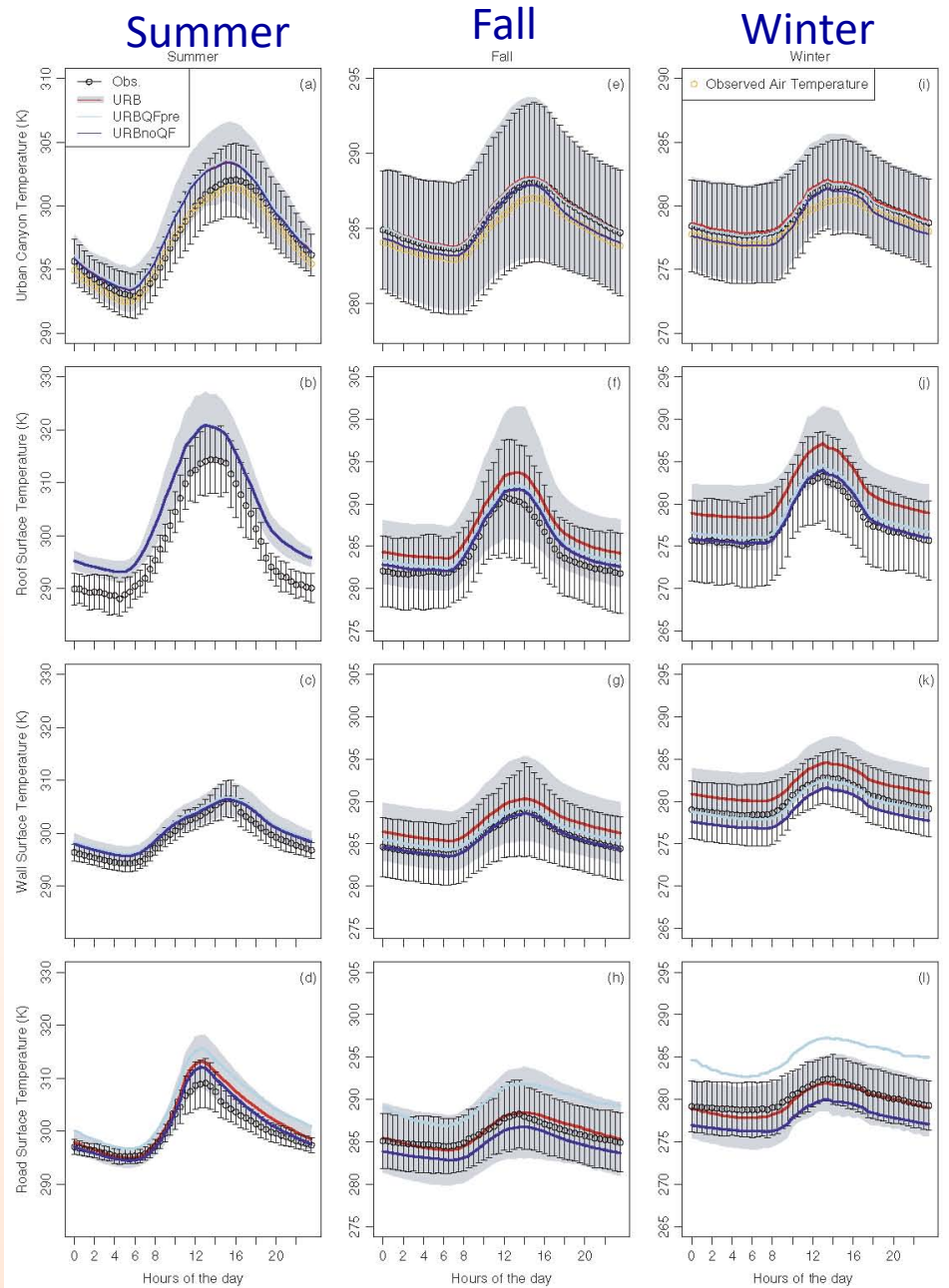
Model Evaluation – Flux Tower Sites

Canyon air temperature

Roof surface temperature

Wall surface temperature

Road surface temperature

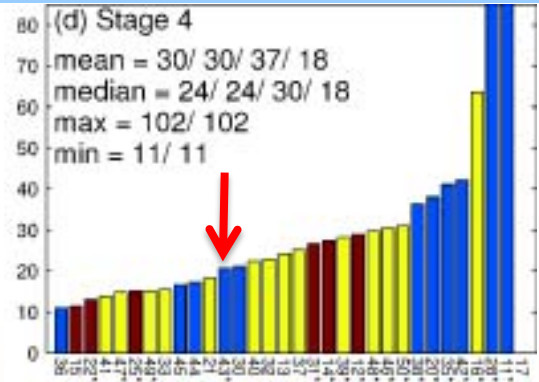
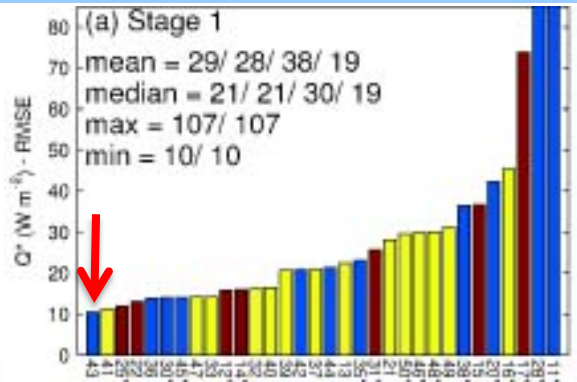


Toulouse
France
2004-2005
(Demuzere et al. 2013)

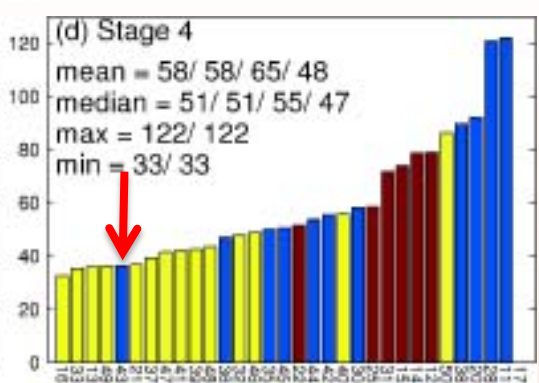
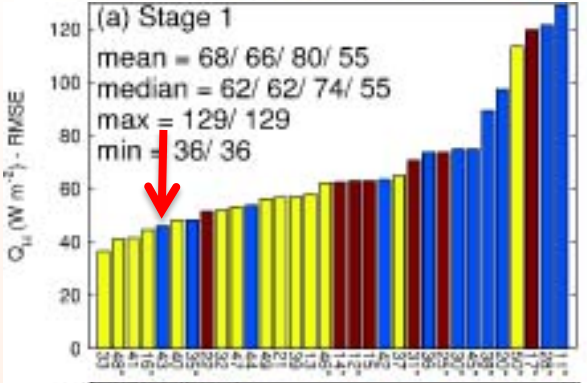
Model Evaluation

International Urban Energy Balance Model Comparison (Grimmond et al. 2010);
 Aug 2003 – Nov 2004 Suburban (Preston) Melbourne, Australia

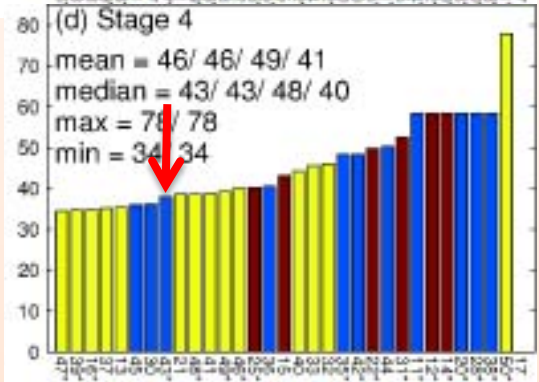
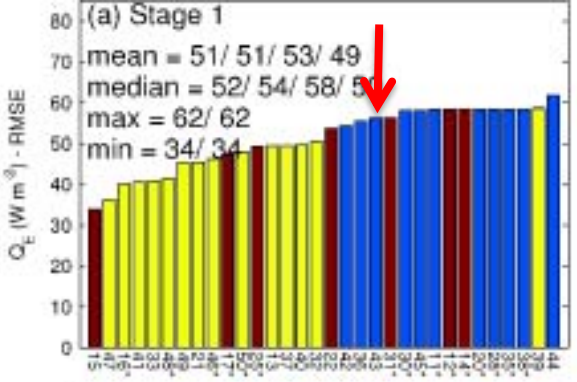
Net Radiation



Sensible Heat

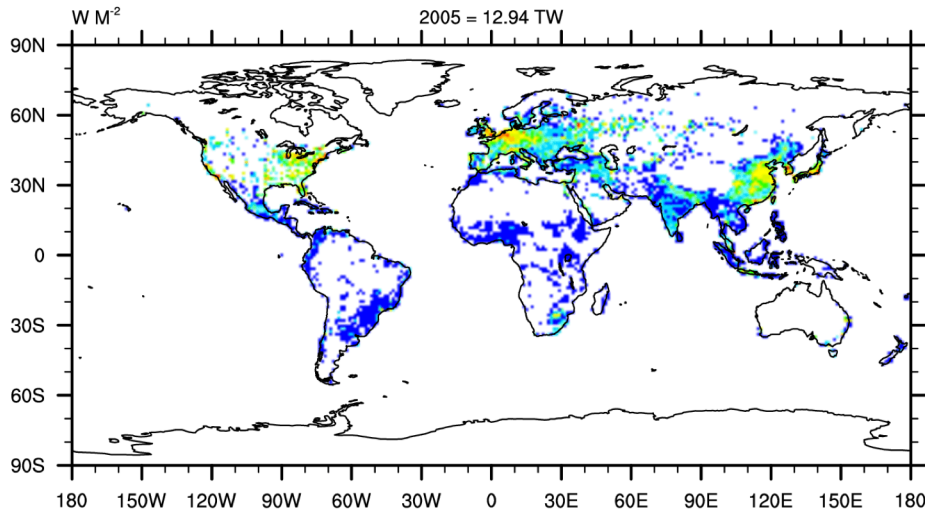


Latent Heat



Evaluation - Anthropogenic Heat Flux

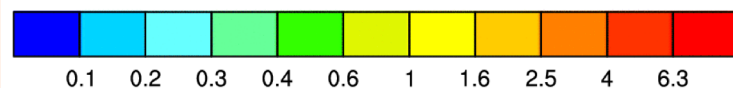
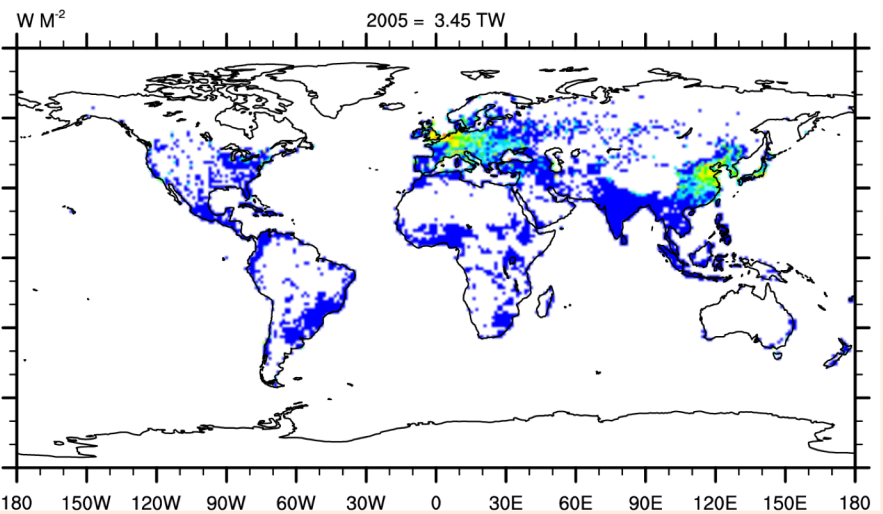
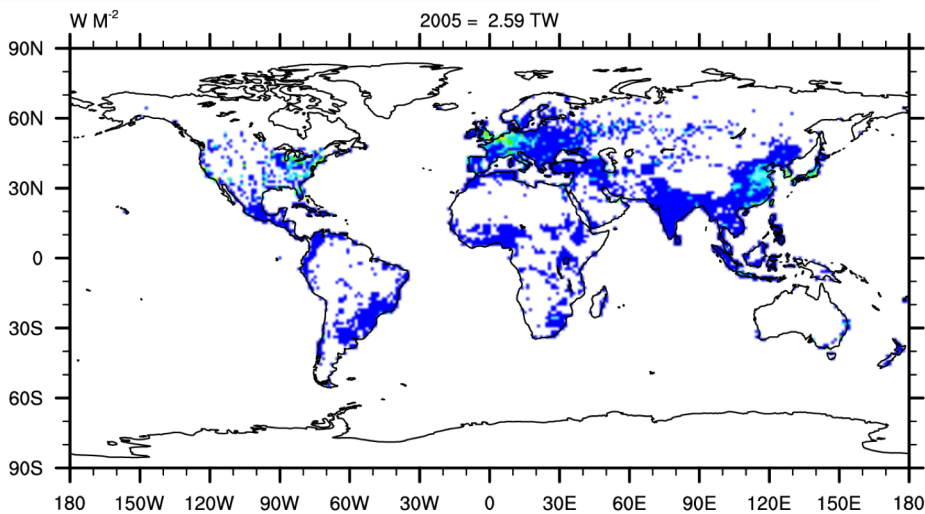
Flanner 2009, GRL



Flanner, 2009: Estimates of annual-mean AHF resulting from consumption of non-renewable energy sources for all uses. Country-specific data of energy consumption apportioned according to population density and converted to annual-mean gridded energy flux.

Estimated annual building heating/cooling energy
 $12.9\text{TW} \times 40\% \times 50\% = 2.6\text{TW}$ (IEA and UNEP)

CLMU



Remote Sensing – Sfc. UHI Relationship to Ecological Setting

FE – Temperate broadleaf and mixed forest (northern)

FA – Temperate broadleaf and mixed forest (southern)

GN – Temperate grasslands, savannahs, and shrublands

DE – Desert and xeric shrublands

MS – Mediterranean forests, woodlands, shrub (California)

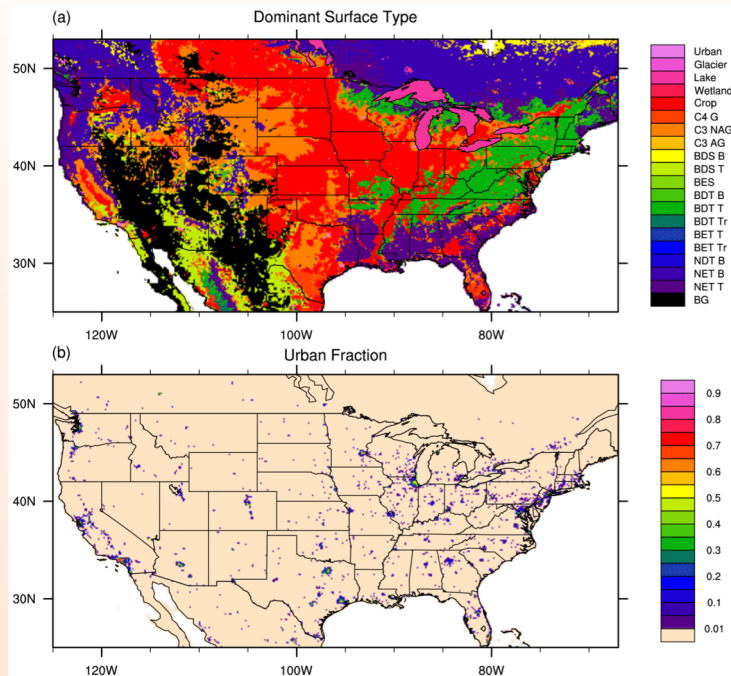
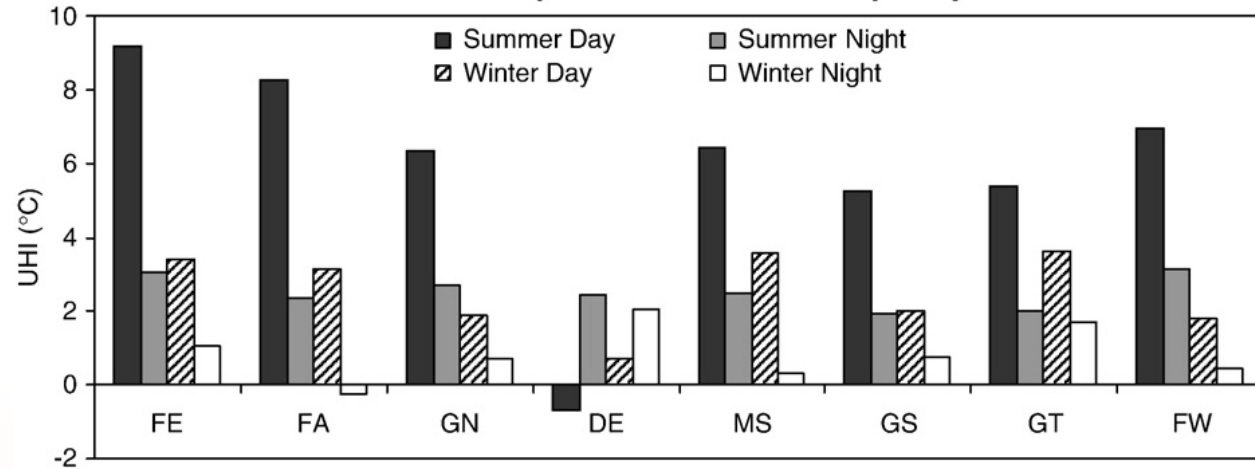
GS – Temperate grasslands, savannahs, and shrublands (Texas)

GT – Tropical and subtropical grasslands, savannahs, and shrublands (Houston, New Orleans)

FW – Temperate coniferous forest (Oregon, Washington)

Imhoff et al. 2010, RSE, Fig. 4

Urban-Rural Temperature for Cities Grouped by Biome



CLMU Daily Average Surface UHI (°C)

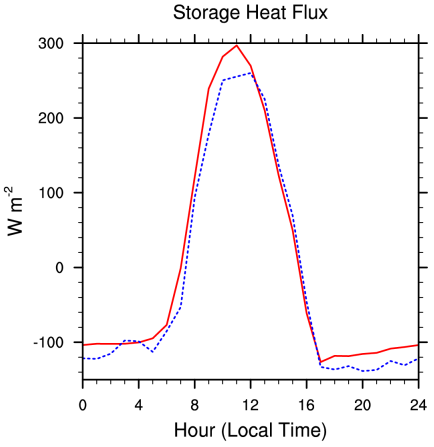
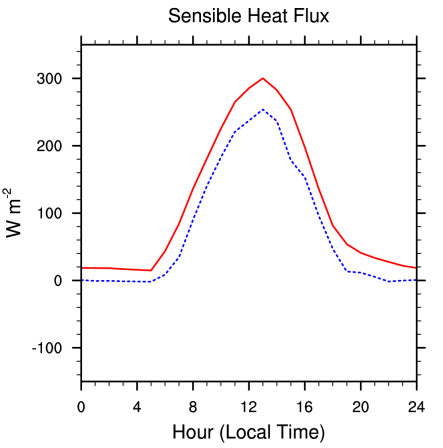
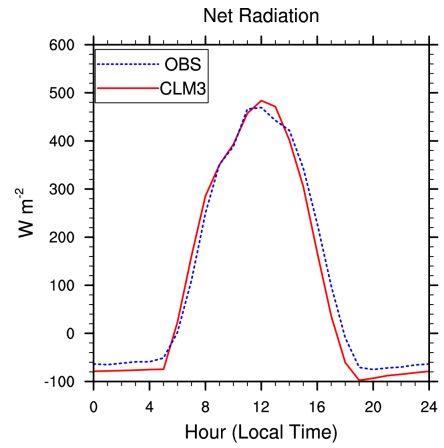
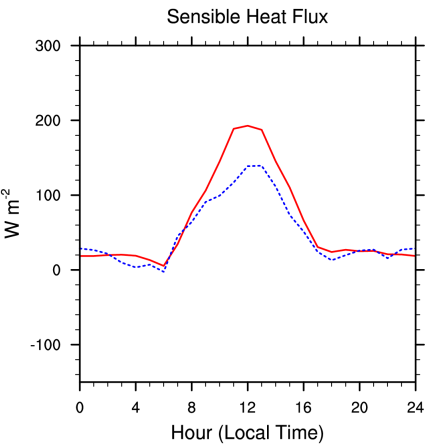
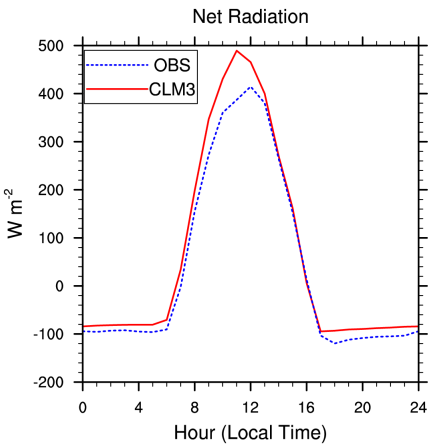
	Summer	Winter
<i>NET</i>	5.7	2.1
<i>BDT</i>	5.3	2.6
<i>Crop</i>	4.7	2.8
<i>C3/C4 Grass</i>	4.7/4.8	2.8/1.6
<i>Bare Ground</i>	4.3	3.2
<i>BDS</i>	3.6	2.2

Model Evaluation

Flux Towers

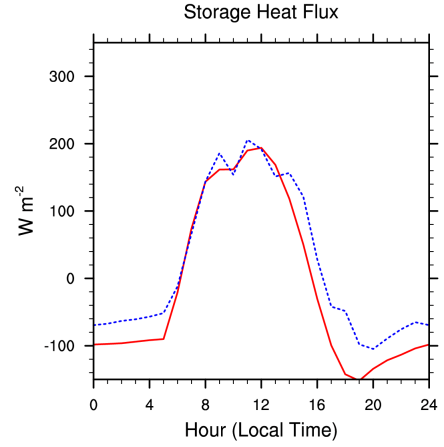
Mexico City - Historic city core
 Oke et al. (1999); Dec 2-7, 1993
 H/W=1.2, H=18m

Vancouver - Light industrial
 Voogt & Grimmond (1999); Aug 20-24, 1992
 H/W=0.4, H=6m



Q_s/Q^*

	OBS	Model
Day	0.58	0.55
Night	1.22	1.25

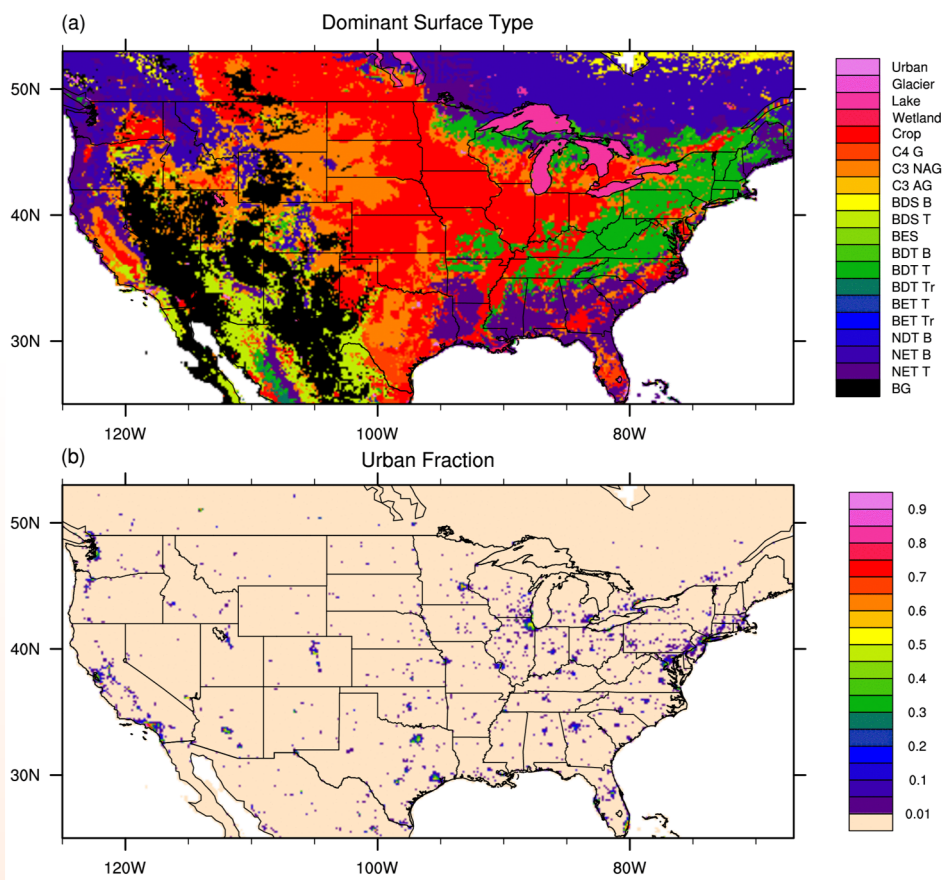


Q_s/Q^*

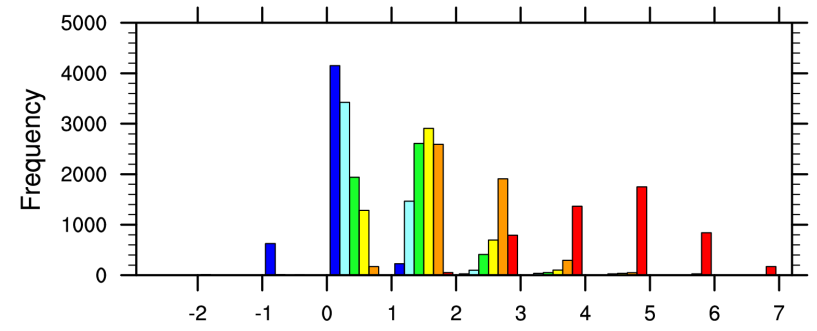
	OBS	Model
Day	0.38	0.32
Night	1.17	1.39

Effects of Urban Density on Urban Heat Island

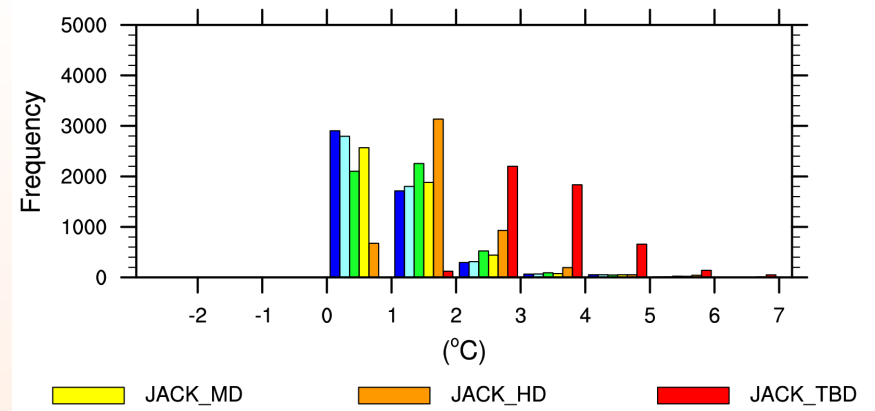
CLM forced by NLDAS (1990-2009)



Urban – Rural MIN Air Temp
DJF



JJA



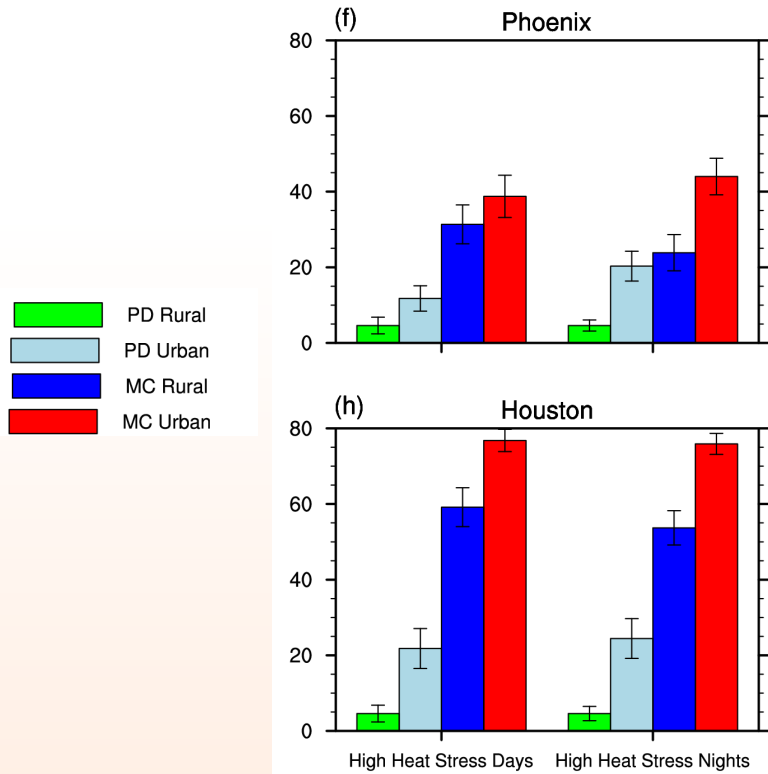
Average Urban – Rural MIN Air Temp (°C)

	JACK_MD	JACK_HD	JACK_TBD
DJF	1.4	2.0	4.1
JJA	1.2	1.7	3.3

Present-day (PD) and Mid-century (MC) High Heat Stress Days and Nights

Number of days per summer with Hlmin and Hlmax exceeding the PD RURAL Hlmin95 and Hlmax95

NWS Heat Index (HI)



Present-day

- High heat stress days and nights occur more frequently in urban than rural areas
- Urban high heat stress occurs more frequently at night (e.g., urban Phoenix has 20 nights with Hlmin above 30°C and 12 days with Hlmax above 42°C)

Mid-century

- Climate change significantly increases the number of high heat stress days and nights in both rural and urban areas, particularly in Houston (e.g., rural Houston has 59 days with Hlmax above 38°C and 54 nights above 30°C; urban Houston has 77 days with Hlmax above 38°C and 76 nights with Hlmin above 30°C).

	Hlmax95 [°C(F)]	Hlmin95 [°C(F)]
Phoenix	42 (108)	30 (86)
Houston	38 (100)	30 (86)

Hypothesis

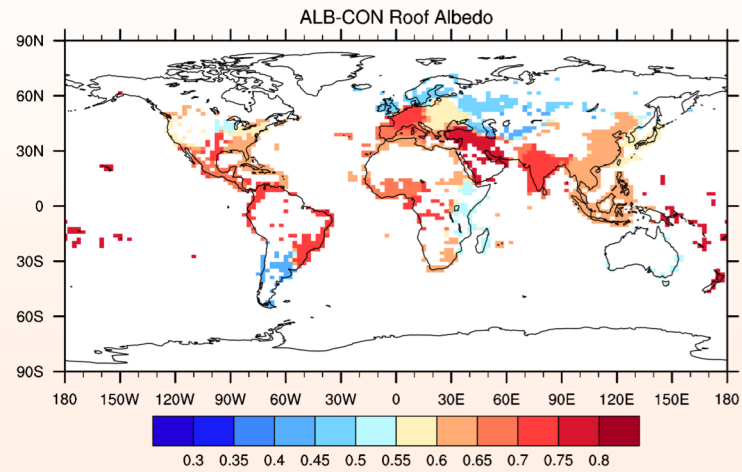
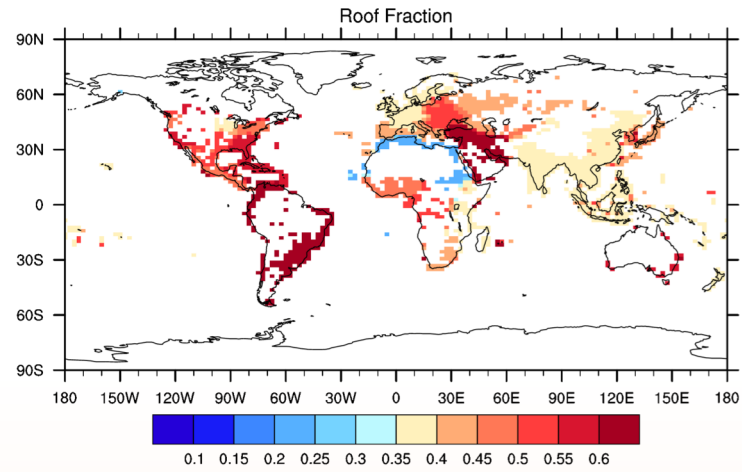
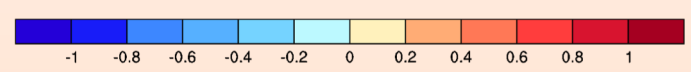
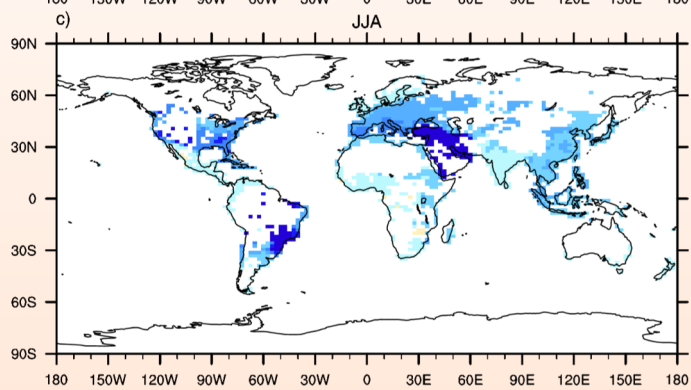
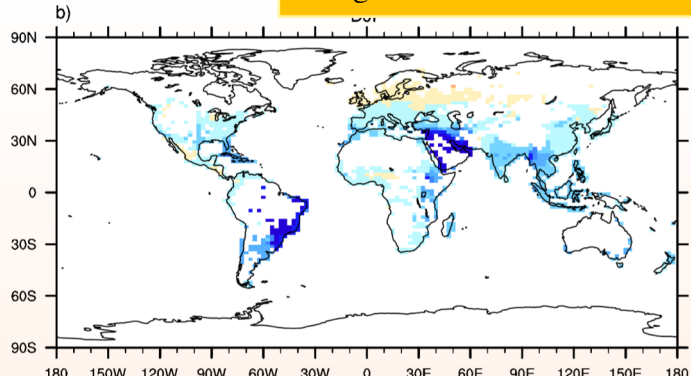
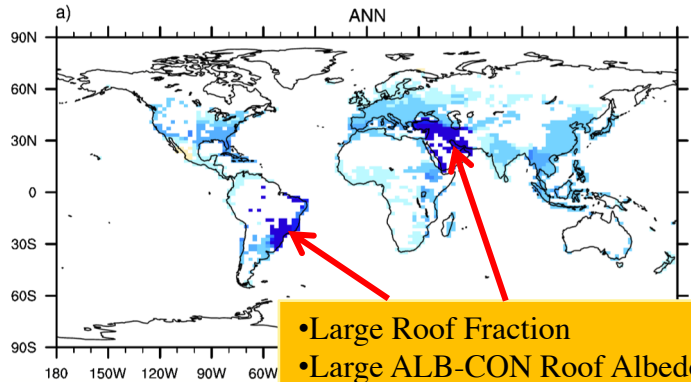
White roofs can reduce the urban heat island effect

- What is the role of roofs in the urban energy budget and their contribution to the urban heat island?
- Identify issues with heat island mitigation using white roofs
- Identify what processes must be considered when evaluating the effectiveness of this UHI mitigation method

Oleson, K.W., G.B. Bonan, and J. Feddema, 2010: The effects of white roofs on urban temperature in a global climate model, *Geophys. Res. Lett.*, 37, L03701, doi:10.1029/2009GL042194.

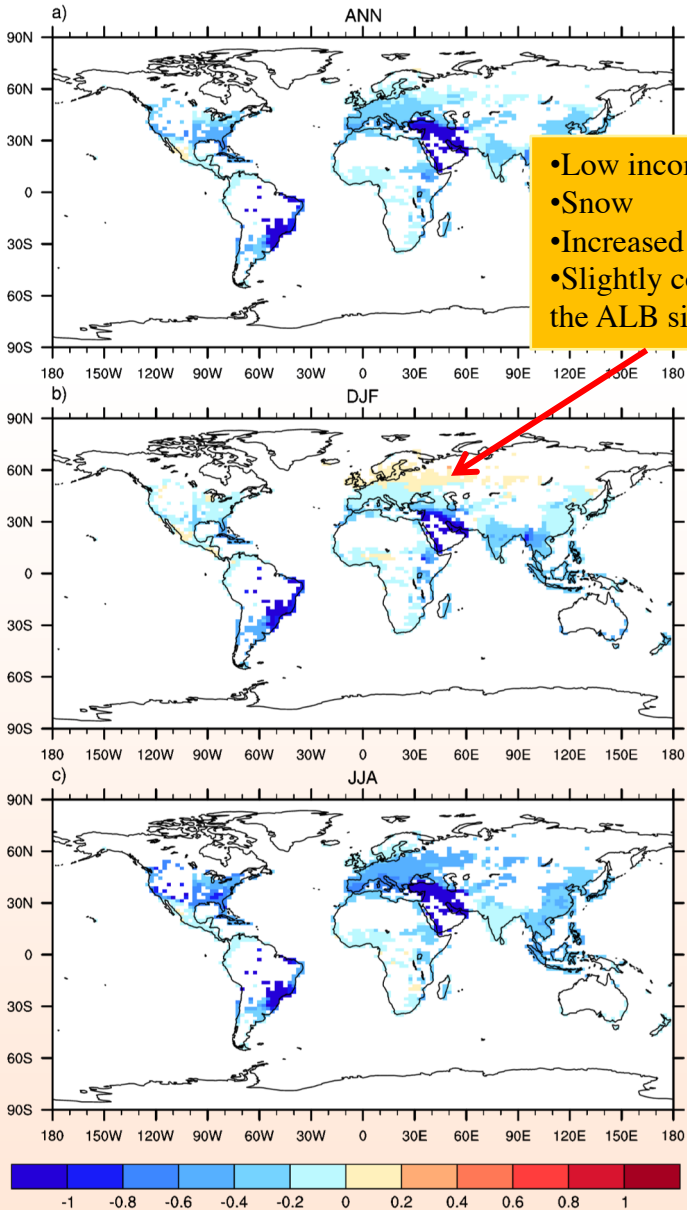
Experiment Results

ALB — CON Urban Heat Island (°C)

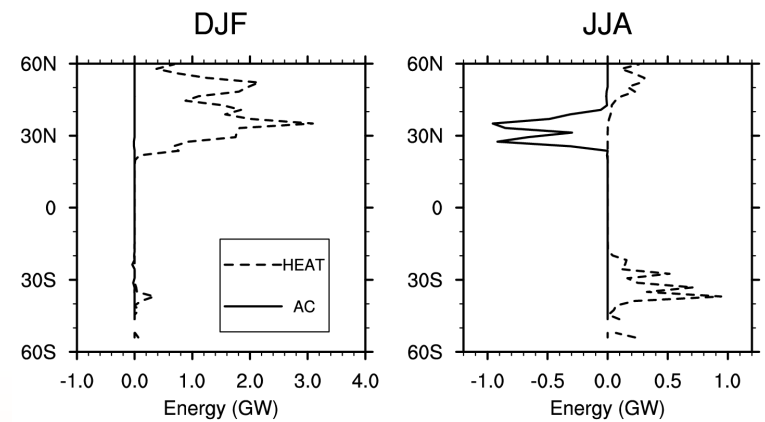


Experiment Results

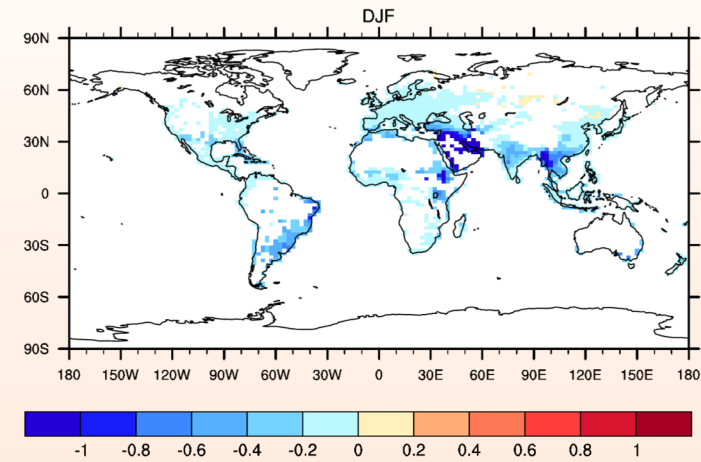
ALB — CON Urban Heat Island (°C)



ALB — CON Space Heating & Air Conditioning



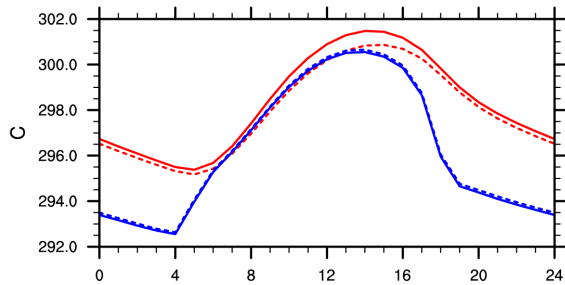
ALB_O — CON_O DJF Urban Heat Island (°C)



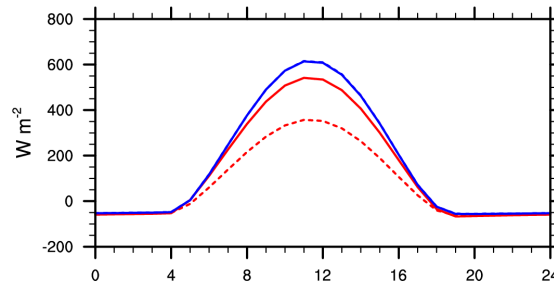
Urban Heat Island Mitigation - White Roofs

JJA average diurnal cycle 40.7N, 287.5E

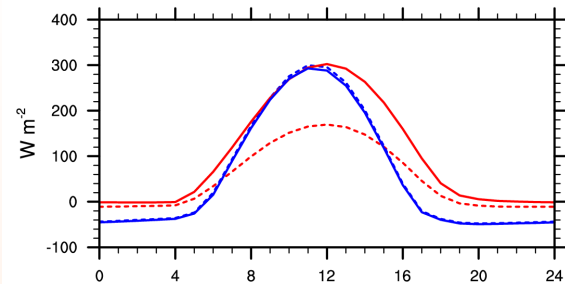
Air Temperature



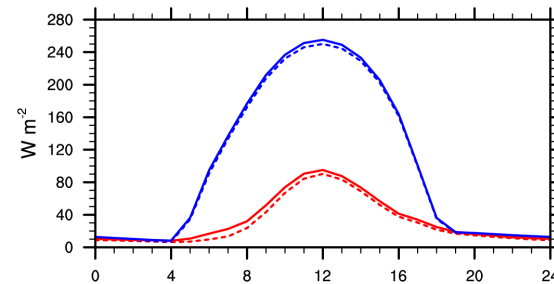
Net Radiation



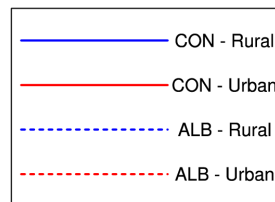
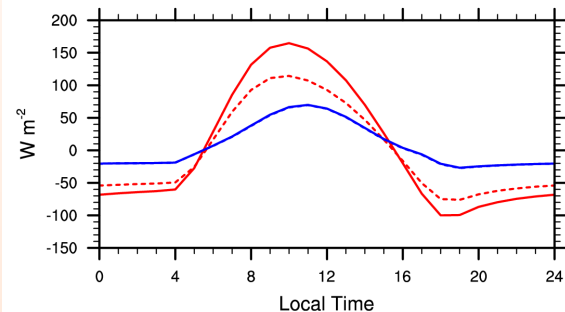
Sensible Heat



Latent Heat



Storage



Effects of white roofs:

- Reduce daytime available energy and sensible heat
- Cools daytime temperatures more than nighttime temperatures
- Cooler daily mean temperature ($-0.5^{\circ}C$)

Mitigation – White Roofs

JJA average diurnal cycle
40.7N, 287.5E

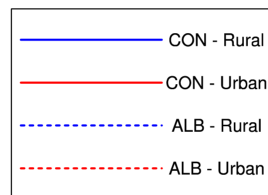
Air Temperature

Net Radiation

Sensible Heat

Latent Heat

Storage



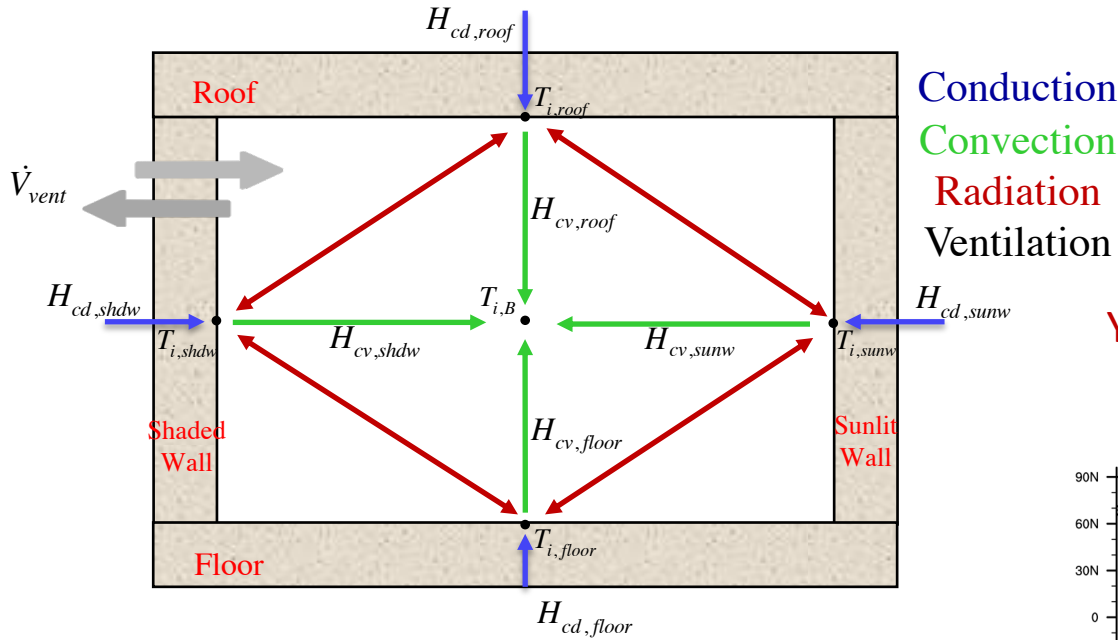
Urban compared to Rural in the control simulation (CON: solid red/blue lines):

- Available energy partitioned into more storage and less latent heat
- Stored heat released at night
- Warmer urban temperatures, particularly at night

Effects of white roofs (ALB-CON: red lines):

- CON Albedo = 0.32
- Reduce daytime available energy, storage, and sensible heat
- Cools daytime temperatures more than nighttime temperatures
- Cooler daily mean temperature (-0.5°C)

Model Evaluation - Anthropogenic Heat Flux

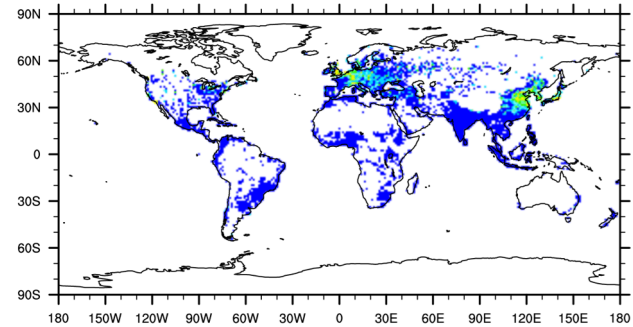


CLMU Building Energy Model

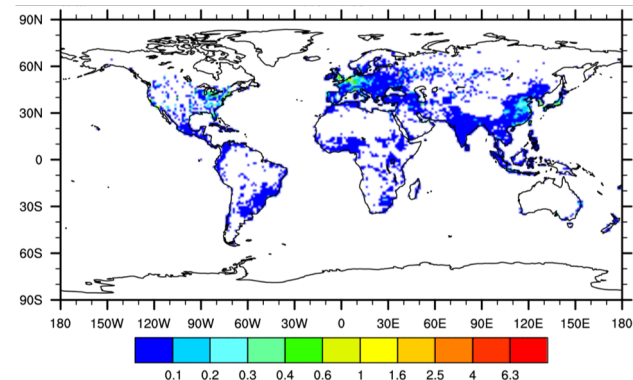
Year 2005 global building heating/cooling energy demand (TW)

Estimated (IEA and UNEP)	3.1
CLMU Version 2	3.0

Year 2005 Anthropogenic Heat Flux ($W m^{-2}$)
CLMU V2

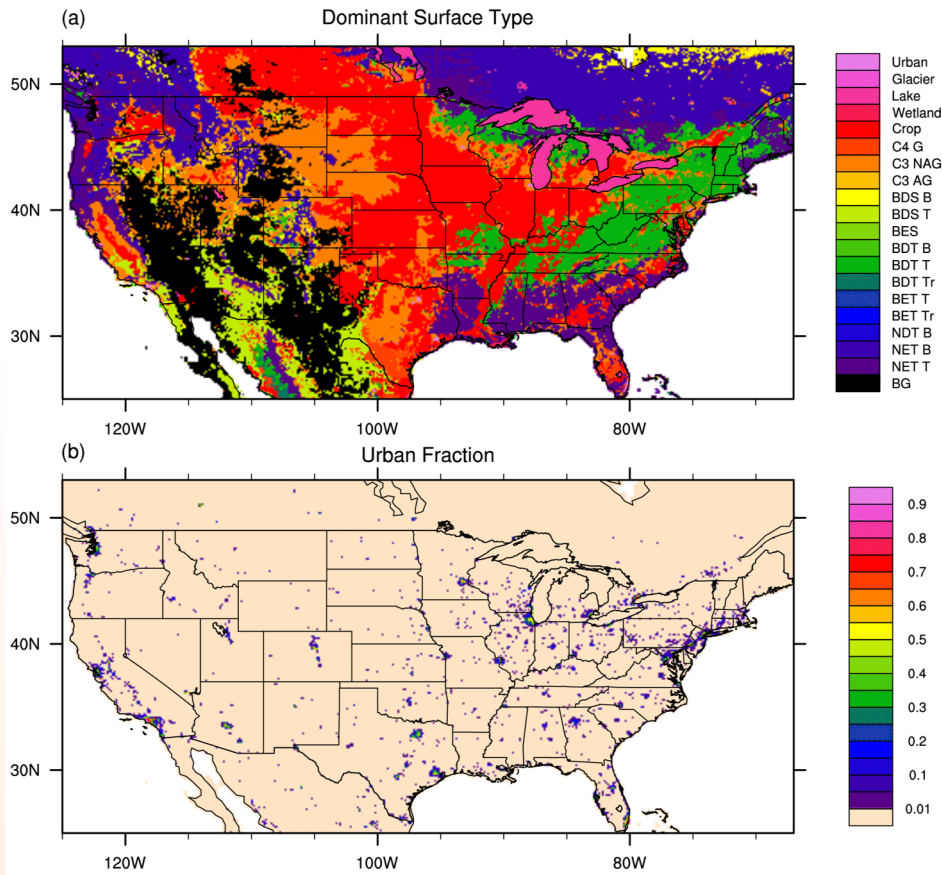


Flanner et al. 2009 (adjusted)

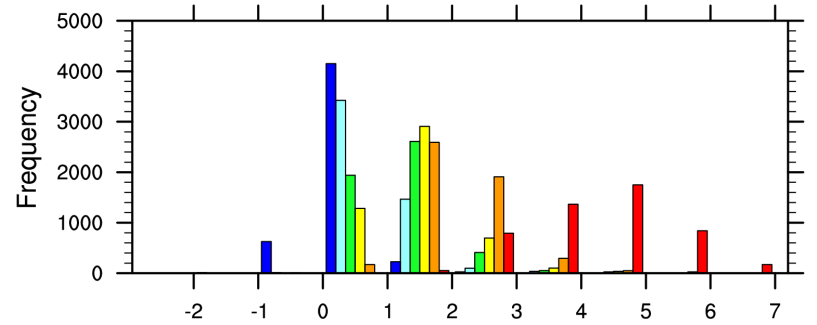


Effects of Urban Density and AHF on UHI

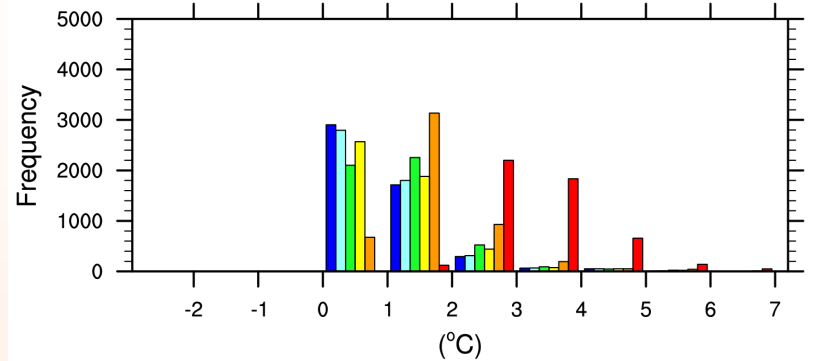
CLM forced by NLDAS (1990-2009)



Urban – Rural MIN Air Temp
DJF



JJA



Average Urban – Rural MIN Air Temp (°C)

	VANC_NOHAC	VANC_HAC	VANC_HACWST	JACK_MD	JACK_HD	JACK_TBD
DJF	0.4	0.9	1.2	1.4	2.0	4.1
JJA	1.1	1.1	1.3	1.2	1.7	3.3

CLMU Development

- Suburban model (low density (LD) urban)
- Integrated urban vegetation model (transpiration, shading of building by trees)
- Irrigation for pervious fraction
- Improved anthropogenic heat fluxes (space heating and cooling, traffic)
- Future urban (dynamic urban landunits – transitions between urban density types; how will cities change – more energy efficient buildings and urban sprawl versus densification)