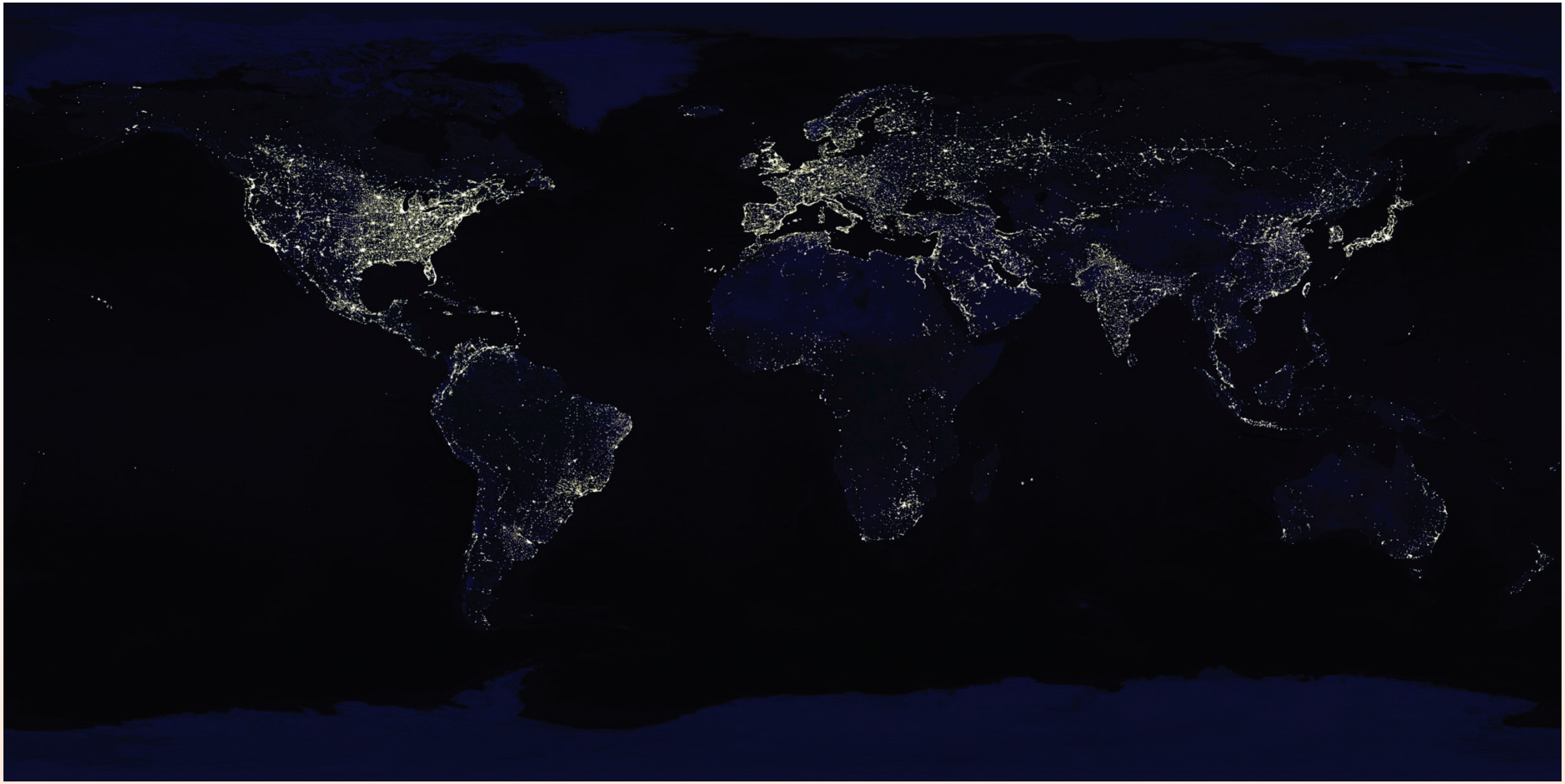
Representing urban areas in climate models: The Community Land Model Urban (CLMU)

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

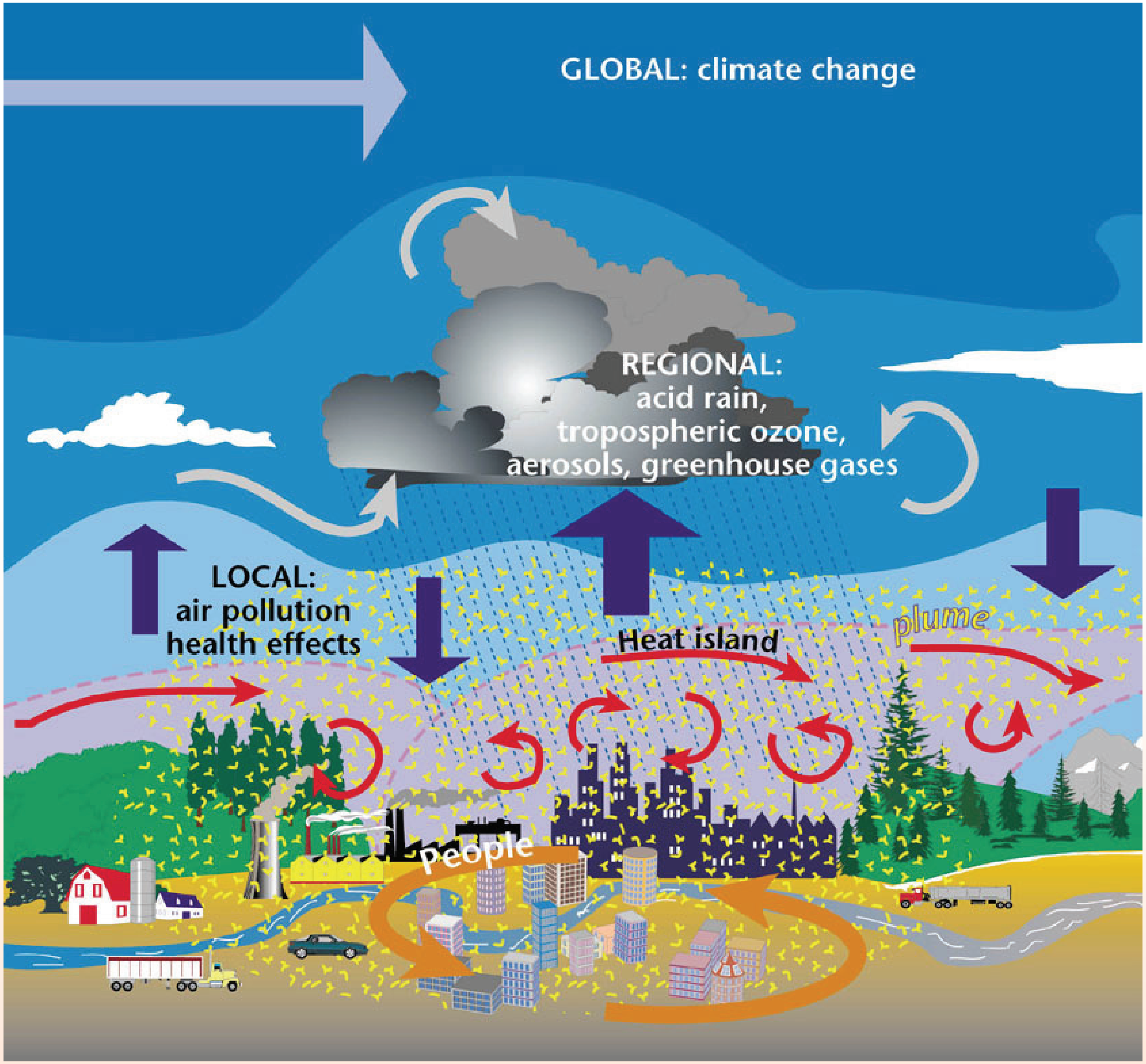


NASA

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)

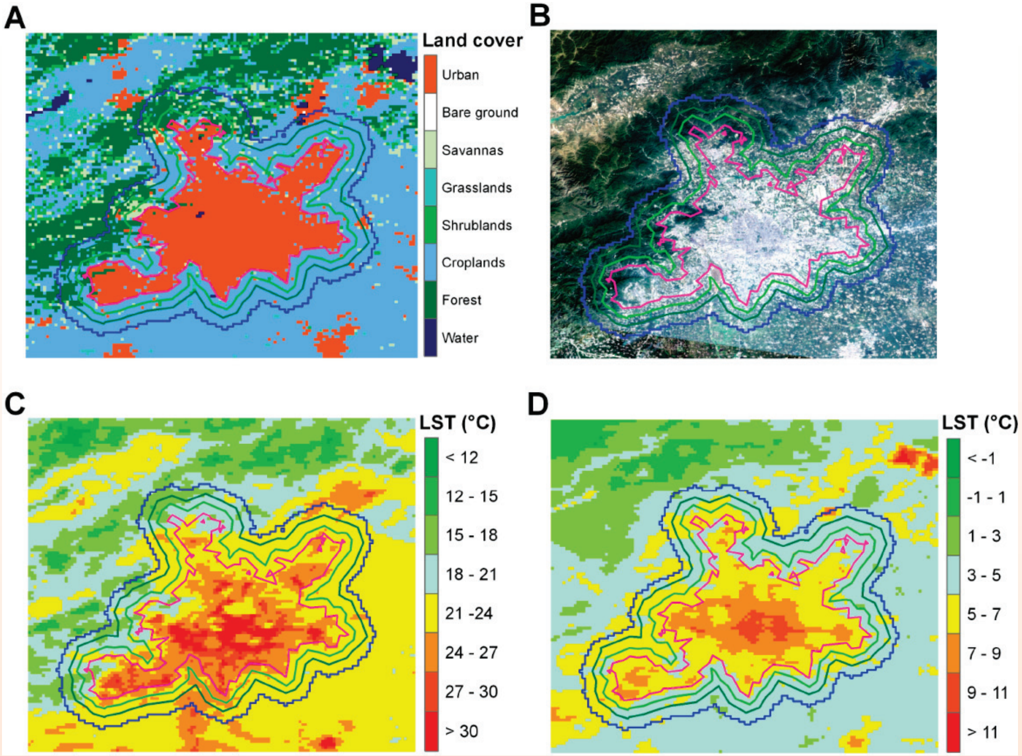
Interactions in the Urban Environment at Various Scales



Hidalgo et al. 2008

The 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.

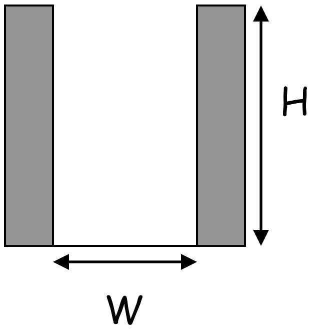


Beijing
(A) MODIS data derived land cover/use
(B) Landsat ETM+ true color image with spatial resolution 30 m × 30 m in August, 2005
(C) annual mean daytime land surface temperature (LST) (°C)
(D) annual mean nighttime LST (°C).

Peng et al (2011)

Urban canyon, H/W

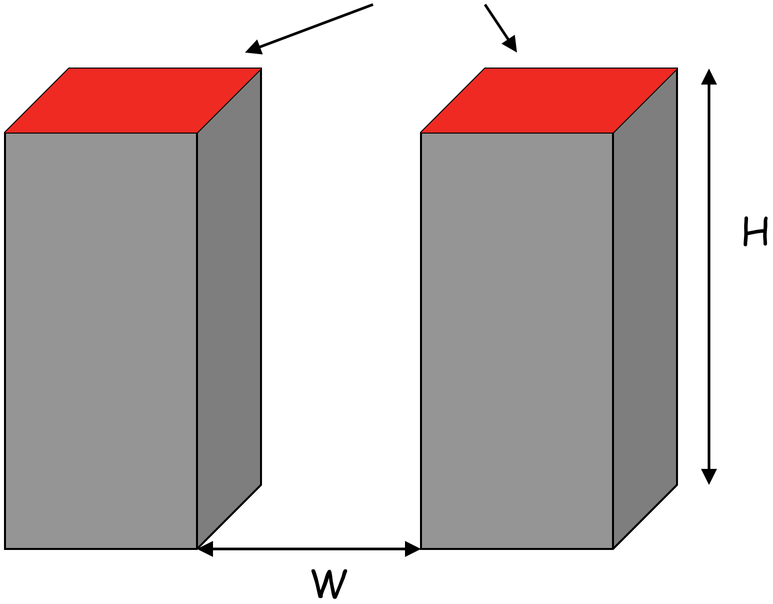
City and residential streets can be characterized by an idealized "canyon" defined by building height H and street width W



Slide courtesy G. Bonan

Roof area, W_{roof}

A substantial surface area is covered by roofs

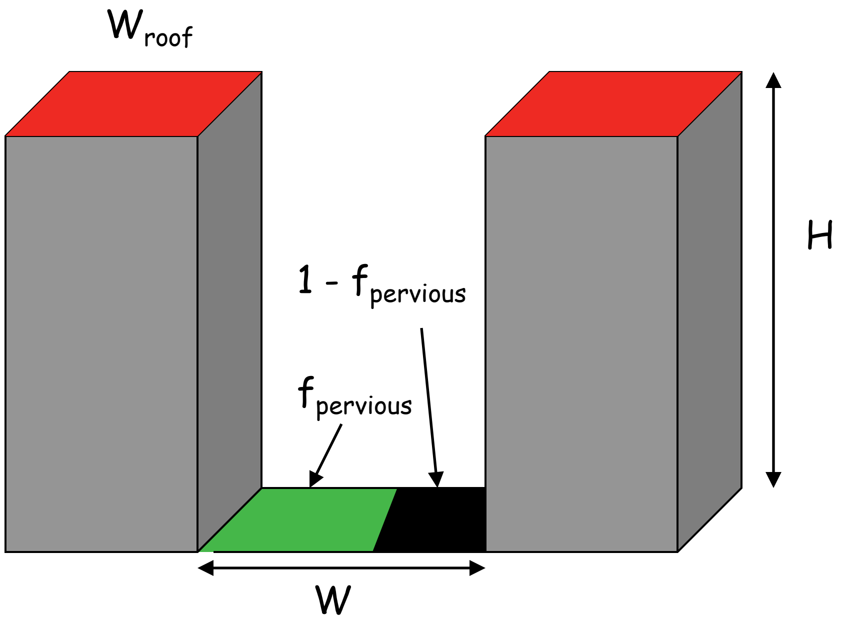


Fraction of city covered by roofs, $0 \le W_{roof} \le 1$

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

Slide courtesy G. Bonan

Urban parks, $f_{pervious}$

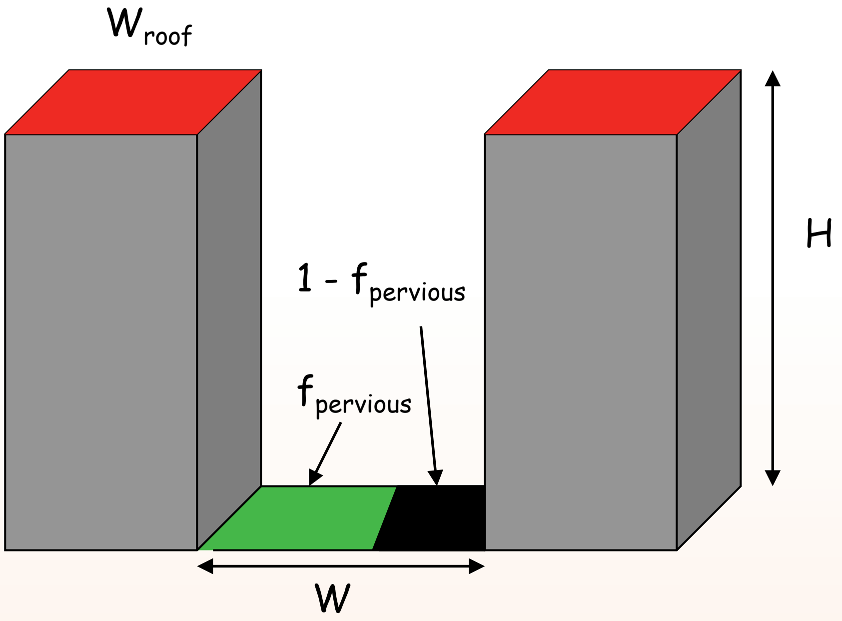


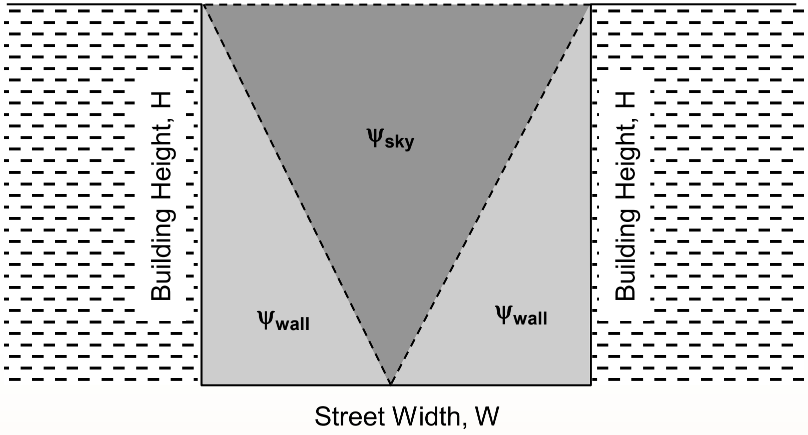
Impervious area = 1 - $f_{pervious}$

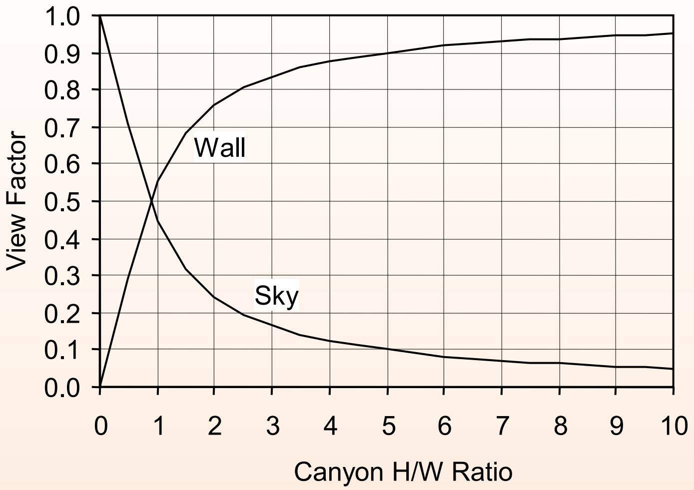
Slide courtesy G. Bonan

Processes contributing to the UHI

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





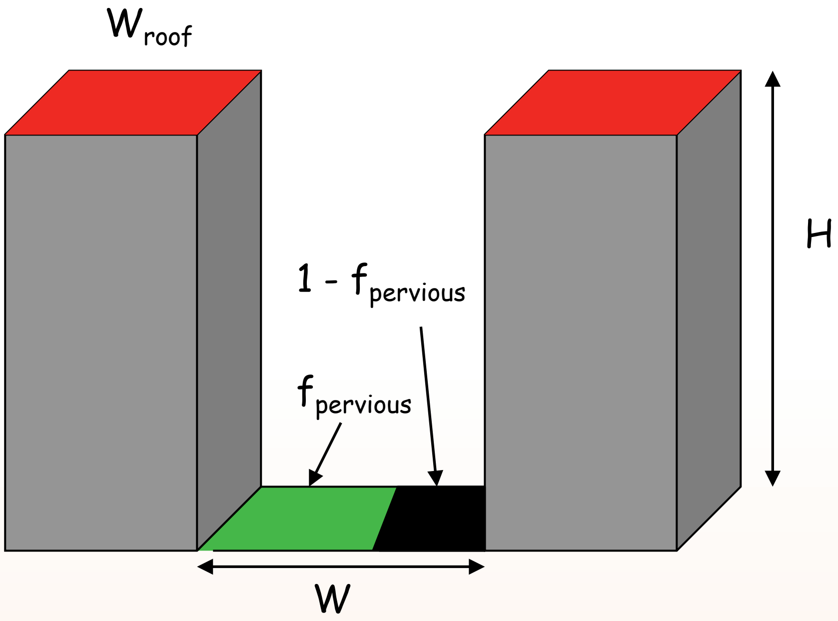


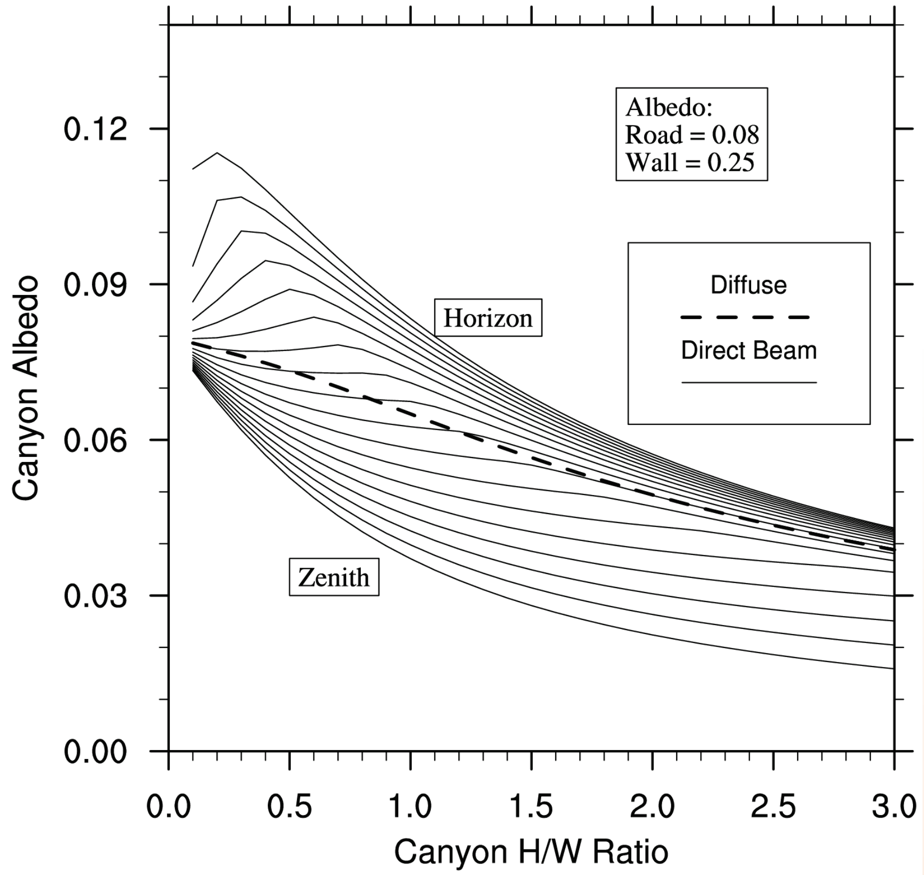
As H/W increases, a point in the street "sees" proportionally less of the sky and more of the wall. More of the longwave radiation emitted by urban surfaces is trapped in the canyon.

Bonan (2008) Ecological Climatology. 2nd edition (Cambridge Univ. Press)

Processes contributing to the UHI

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





Oleson et al. (2008)

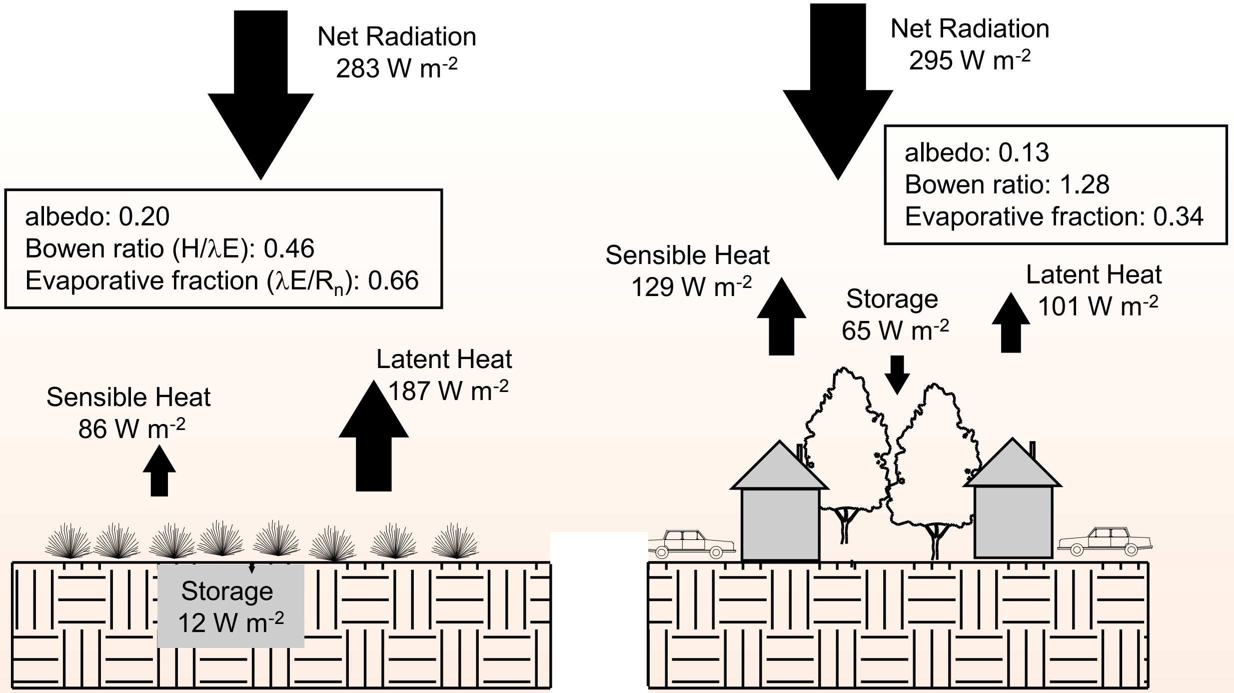
- Direct and diffuse canyon albedo decreases with height to width ratio so that more solar radiation is trapped and absorbed within the canyon.

- 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

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



Net Radiation
283 W m^{-2}

albedo: 0.20
Bowen ratio ($H/\lambda E$): 0.46
Evaporative fraction ($\lambda E/R_n$): 0.66

Sensible Heat
86 W m^{-2}

Latent Heat
187 W m^{-2}

Storage
12 W m^{-2}

Net Radiation
295 W m^{-2}

albedo: 0.13
Bowen ratio: 1.28
Evaporative fraction: 0.34

Sensible Heat
129 W m^{-2}

Storage
65 W m^{-2}

Latent Heat
101 W m^{-2}

Rural: managed grassland

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

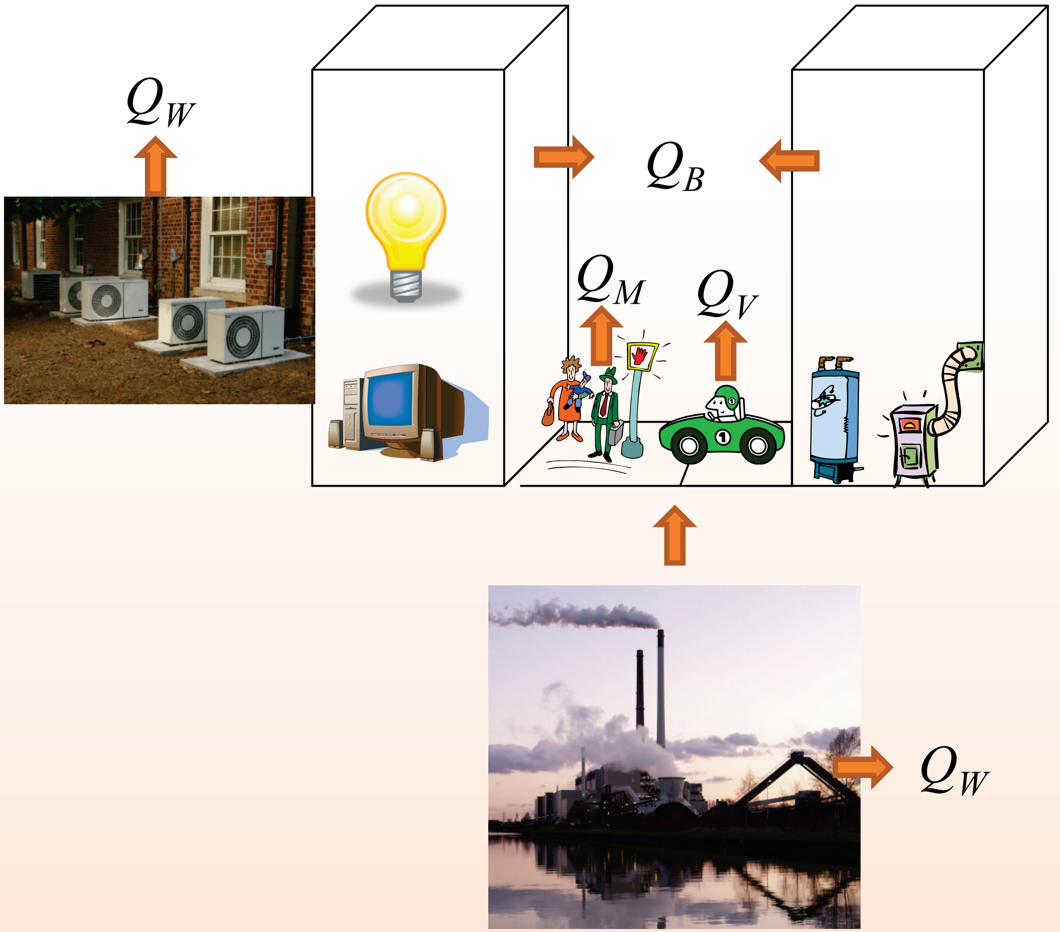
Cleugh & Oke (1986)

Figure courtesy G. Bonan

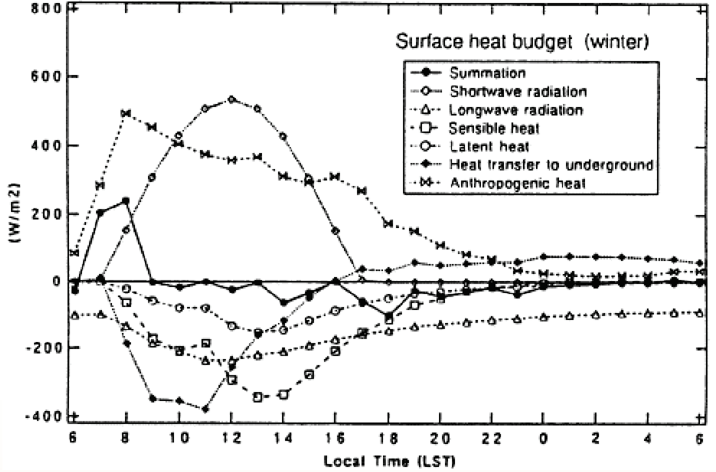
Processes contributing to the UHI

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

$$Q_F = Q_B + Q_V + Q_M + Q_W$$

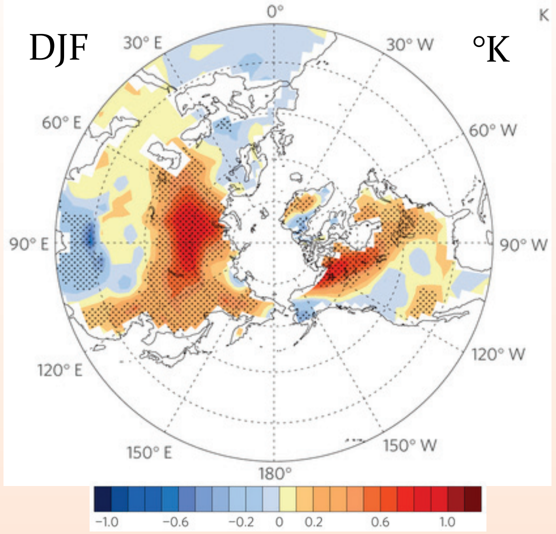


Winter surface energy budget in central Tokyo



Ichinose et al. (1999)

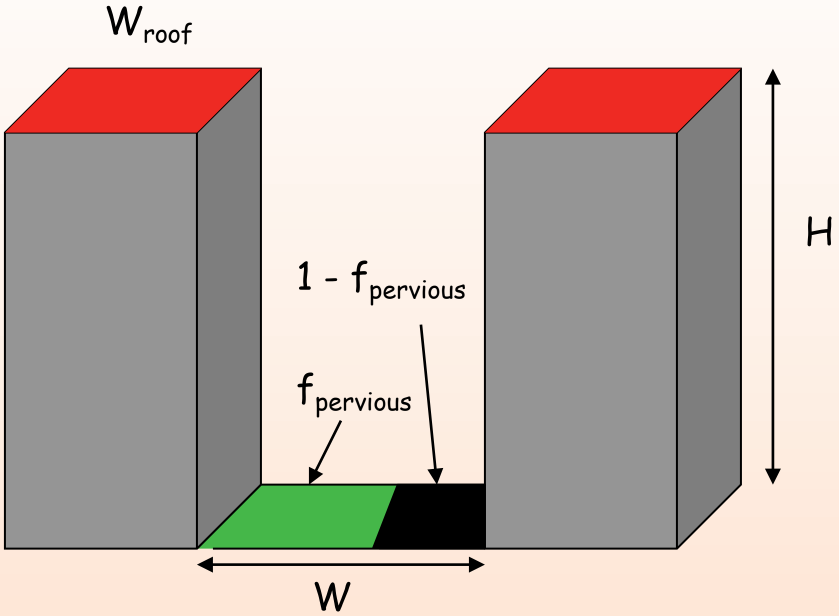
Mean surface air temperature difference



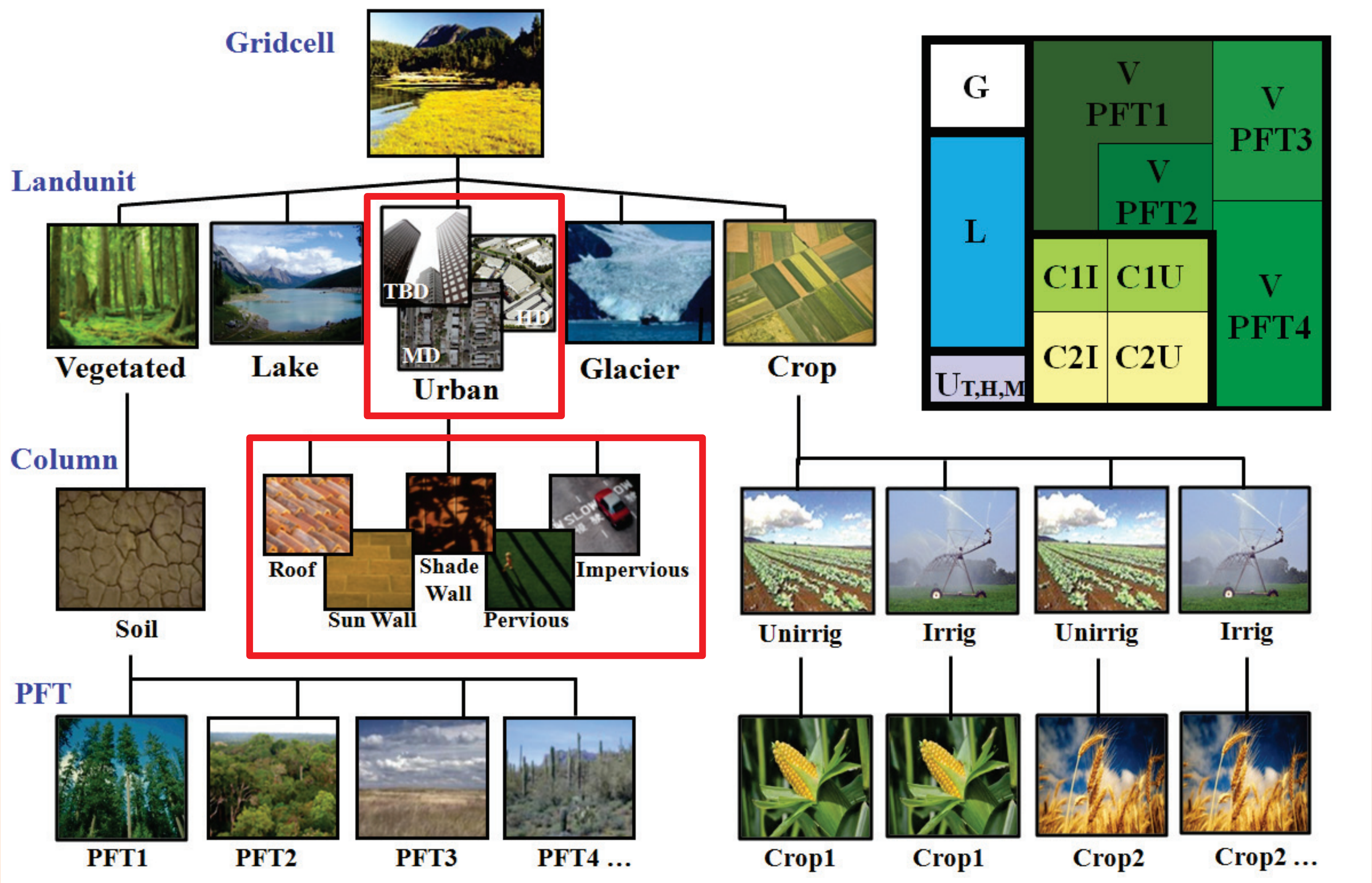
Zhang et al. (2013)

Processes contributing to the UHI

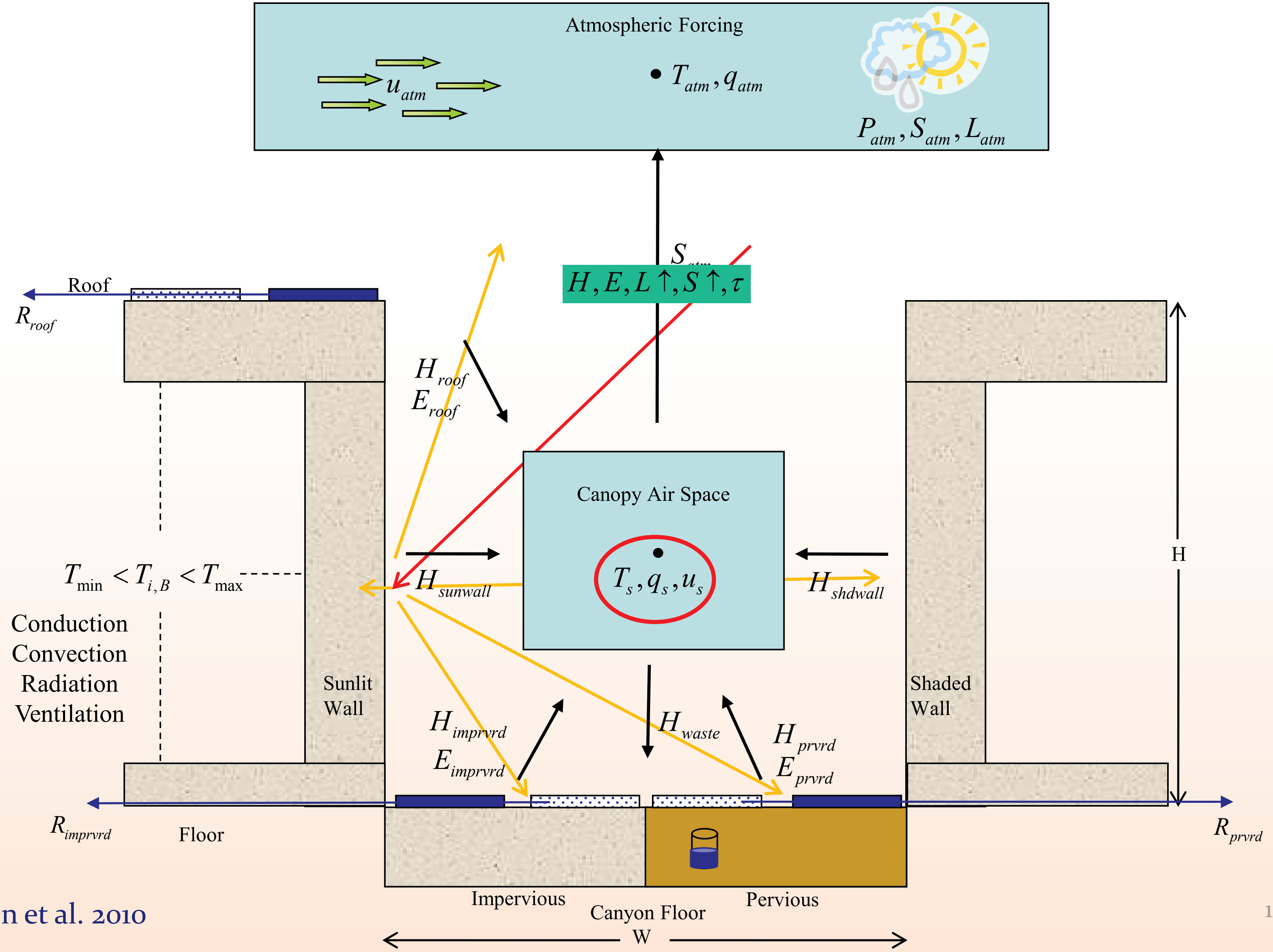
- Increased shortwave absorption due to trapping inside urban canyon (lower albedo)
- Decreased surface longwave radiation loss due to reduction of sky view factor
- Reduction of ET due to replacement of vegetation with impervious surfaces
- Increased storage of heat due to larger heat capacity of urban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



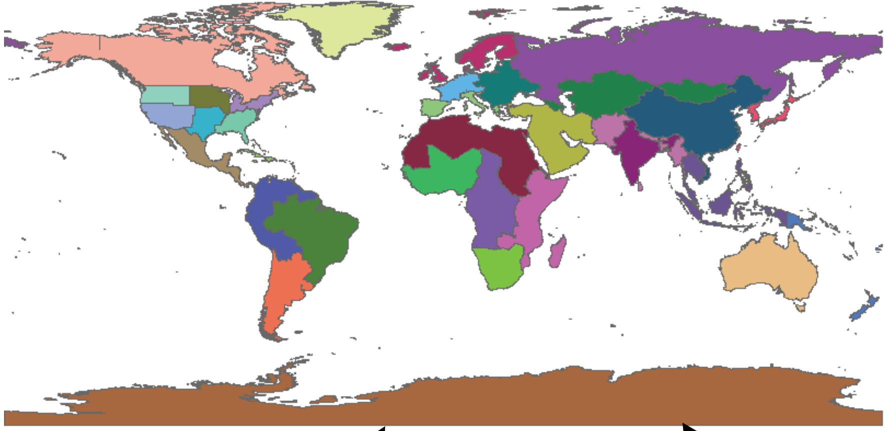
Community Land Model Urban



Oleson et al. 2010

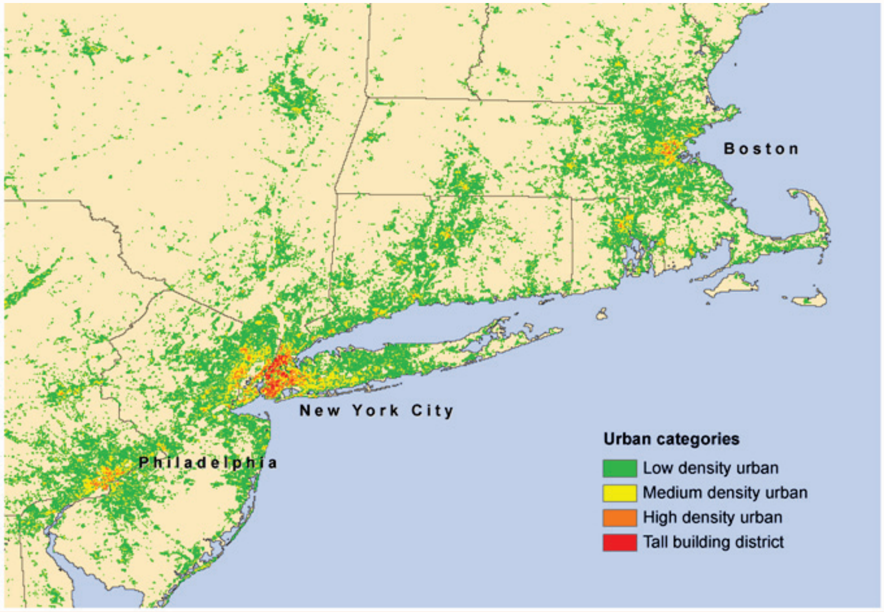
Global Urban Characteristics Dataset

Global Regions



→ **To CLMU**

Urban Extent - Landscan 2004



Jackson et al. 2010

Urban Properties – Compilation of building databases

Morphological

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

Radiative – Roof/Wall/Road

- ***Albedo***
- ***Emissivity***

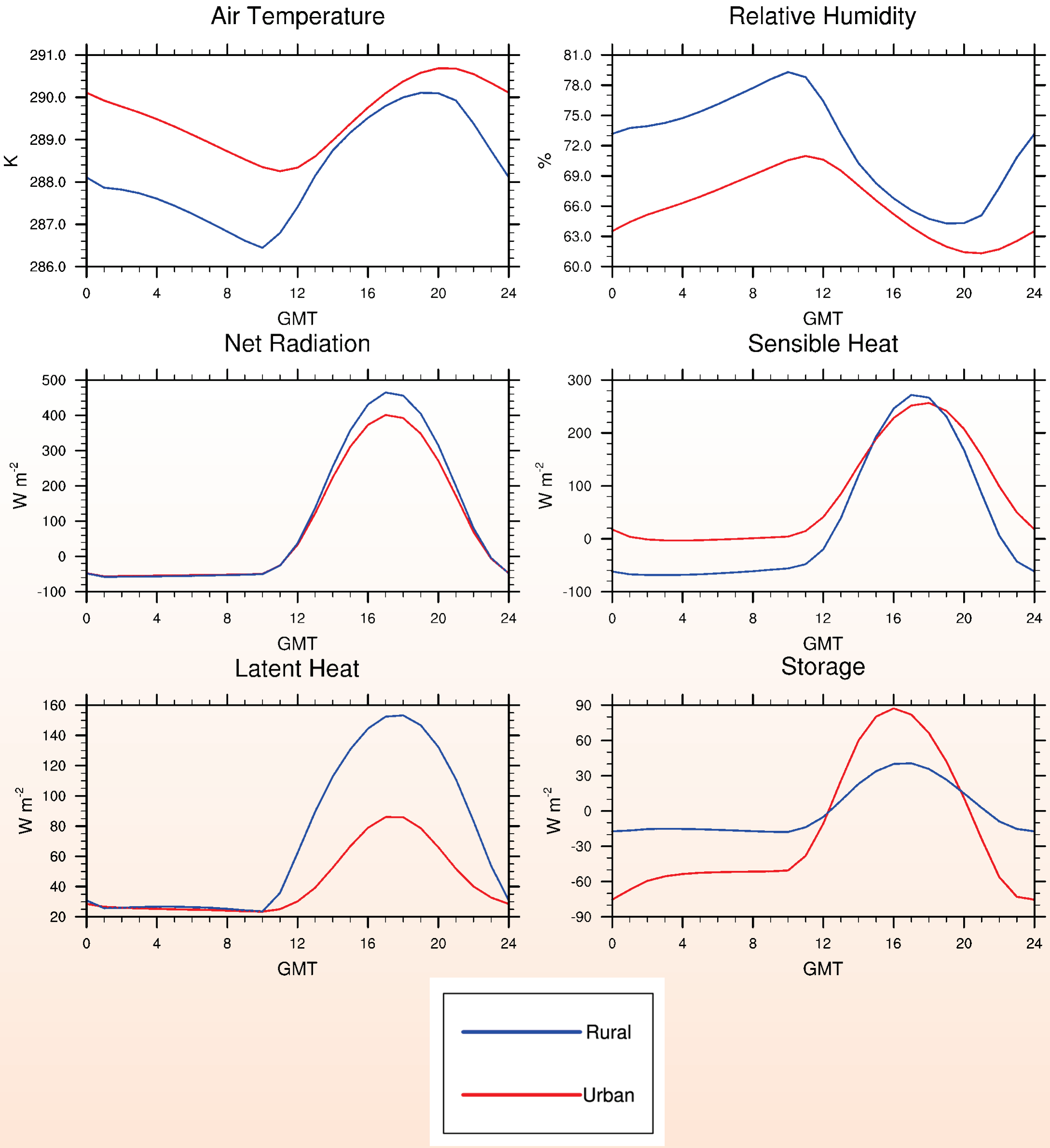
Thermal – Roof/Wall/Road

- ***Conductivity***
- ***Heat Capacity***

Interior temperature settings (HAC)

Modeled Urban and Rural Energy Balance

Annual Average Diurnal Cycle

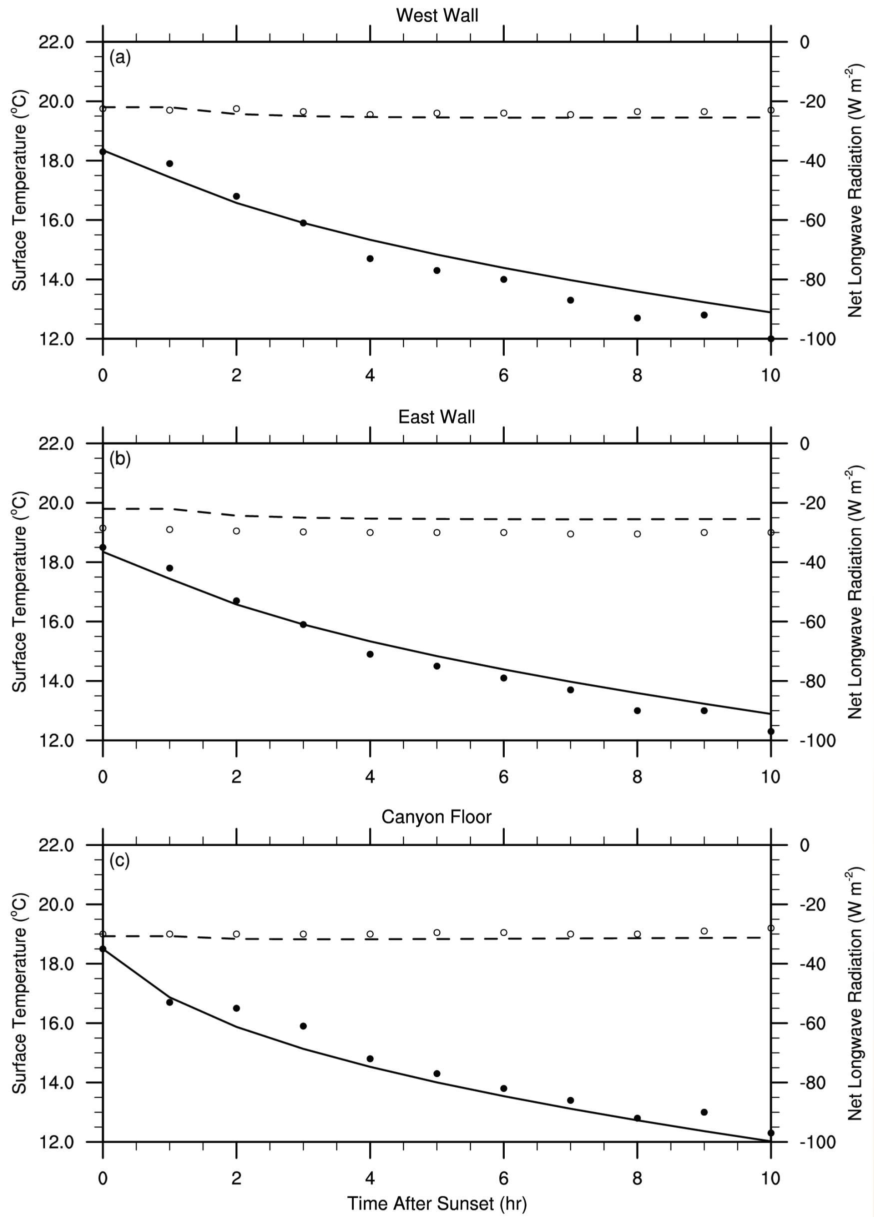


- •Urban area stores more heat during daytime and releases heat at night resulting in nighttime heat island

- •Urban has lower latent heat due to impervious surfaces which contributes to heat island

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 (49ºN, 123ºW) (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

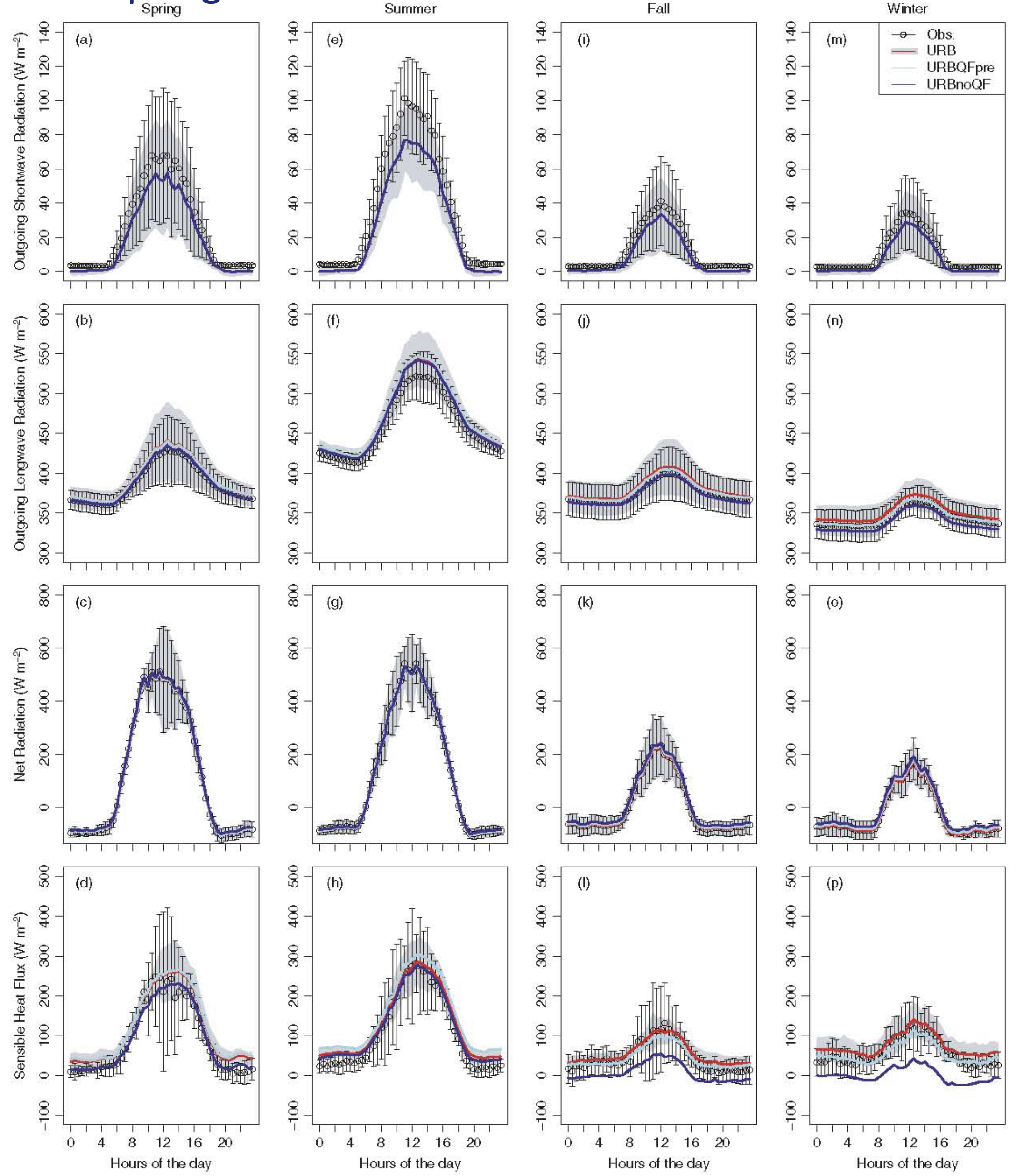
Spring Summer Fall Winter

Outgoing shortwave radiation

Outgoing longwave radiation

Net Radiation

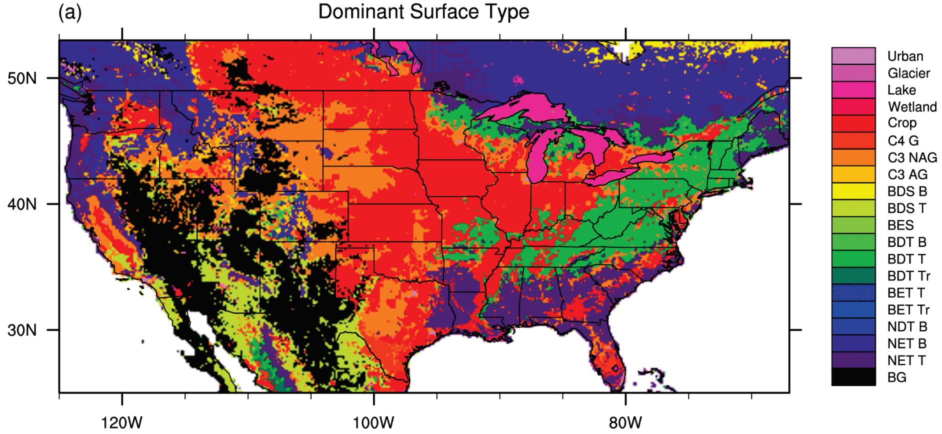
Sensible Heat Flux

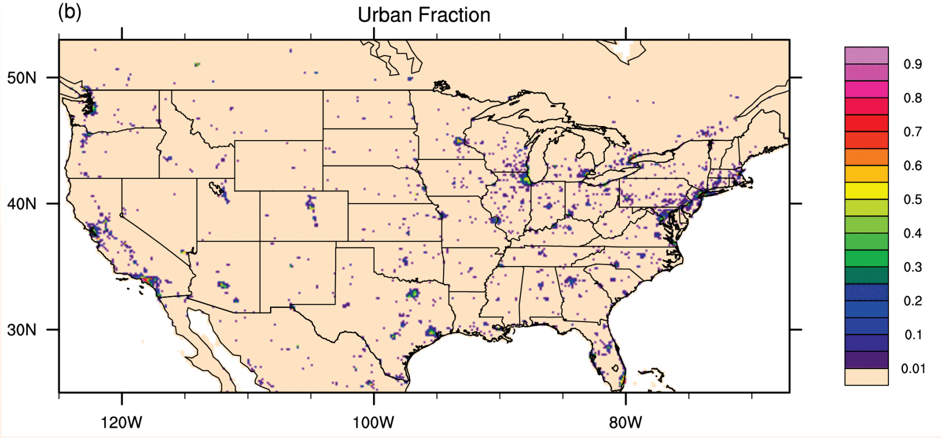


Toulouse
France
2004-2005
(Demuzere
et al. 2013)

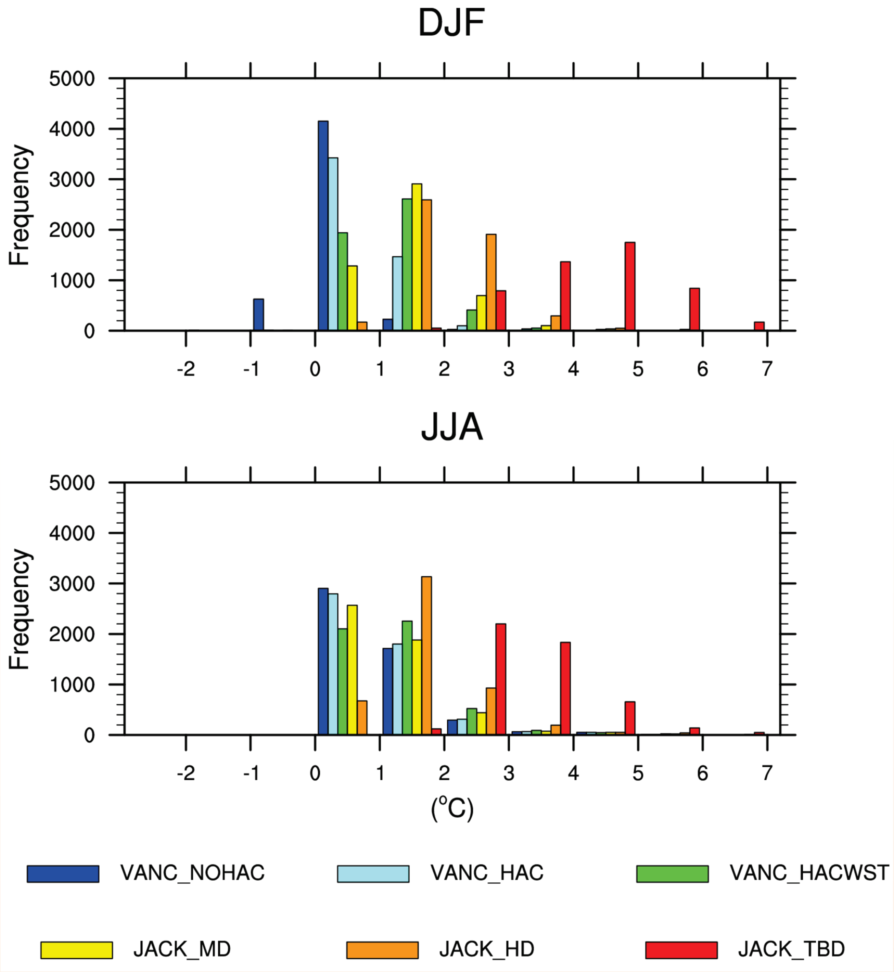
Effects of Urban Density and AHF on UHI

CLM forced by NLDAS (1990-2009)





Urban – Rural MIN Air Temp



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

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

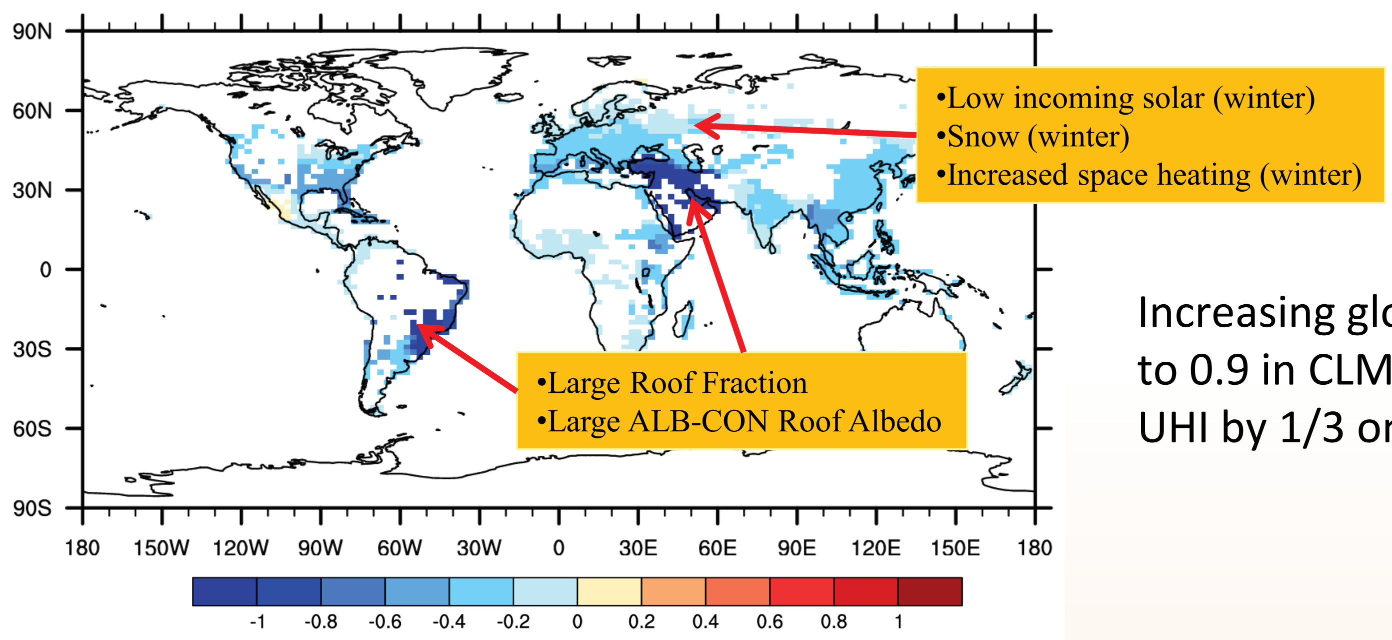
Rooftop gardens

White roofs

Green parking lots

Urban Heat Island Mitigation - White Roofs

Reduction in the annual mean Heat Island (°C)



- Low incoming solar (winter)
- Snow (winter)
- Increased space heating (winter)

- Large Roof Fraction
- Large ALB-CON Roof Albedo

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.

Oleson et al. (2010)

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.

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)

CLMU Publications

- Oleson, K.W., A. Monaghan, O. Wilhelmi, M. Barlage, N. Brunsell, J. Feddema, L. Hu, and D.F. Steinhoff, 2013: Interactions between urbanization, heat stress, and climate change, *Climatic Change*, DOI:10.1007/s10584-013-0936-8.
- 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.
- 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.
- 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.

Thank You

The NESL Mission is:
To advance understanding of weather, climate, atmospheric composition and processes;
To provide facility support to the wider community; and,
To apply the results to benefit society.

NCAR is sponsored by the National Science Foundation