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

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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.
Interactions in the Urban Environment at Various Scales

GLOBAL: climate change
REGIONAL: acid rain, tropospheric ozone, aerosols, greenhouse gases
LOCAL: air pollution health effects
Heat island
plume

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 $1^\circ-3^\circ$C but may reach up to $12^\circ$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) ($^\circ$C)
(D) annual mean nighttime LST ($^\circ$C).

Peng et al (2011)
City and residential streets can be characterized by an idealized “canyon” defined by building height $H$ and street width $W$. 

Slide courtesy G. Bonan
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

Slide courtesy G. Bonan
Urban parks, $f_{\text{pervious}}$

**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**

Rural: managed grassland

- albedo: 0.20
- Bowen ratio (H/LE): 0.46
- Evaporative fraction (LE/Rn): 0.66

- Sensible Heat: 86 W m⁻²
- Latent Heat: 187 W m⁻²
- Storage: 12 W m⁻²

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

- 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

Figure courtesy G. Bonan

Cleugh & Oke (1986)
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

Mean surface air temperature difference

Zhang et al. (2013) Ichinose et al. (1999)
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

Atmospheric Forcing

$T_{\text{atm}}, q_{\text{atm}}$

$P_{\text{atm}}, S_{\text{atm}}, L_{\text{atm}}$

Conduction
Convection
Radiation
Ventilation

$T_{\text{min}} < T_{i,B} < T_{\text{max}}$

Canopy Air Space

$T_s, q_s, u_s$

Roof

Sunlit Wall

Shaded Wall

Floor

Impervious

Pervious

Oleson et al. 2010
Global Urban Characteristics Dataset

Urban Extent - Landscan 2004

Global Regions

To CLMU

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 2019, in review
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)

- 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
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).
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

Oleson and Feddema 2019, in review
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

Feddema et al. 2019, in prep
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
Better insulation reduces heating where required

Feddema et al. 2019, in prep
LtWt: annual temperature change

Less heat absorbed, drives higher surface and air temps

T-max change

Less stored heat released at night reduces temp

Feddema et al. 2019, in prep
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.


CLMU Publications

Thank You!

Questions?
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.

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)
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 20\textsuperscript{th} 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)*

PD: 0.73 °C

CONTROL

DENSITY

-0.07 °C

0.42 °C

DENSITY + 3P WINDOWS

0.59 °C

Legend:
- x < -0.8
- -0.8 <= x < -0.6
- -0.6 <= x < -0.4
- -0.4 <= x < -0.2
- 0 <= x < 0.2
- 0.2 <= x < 0.4
- 0.4 <= x < 0.6
- 0.6 <= x < 0.8
- x >= 0.8

**PD:** 1.26 °C

**CONTROL**

-0.01 °C

**DENSITY**

0.03 °C

**DENSITY + 3P WINDOWS**

-0.47 °C

Legend:
- $x < -0.8$
- $-0.8 \leq x < -0.6$
- $-0.6 \leq x < -0.4$
- $-0.4 \leq x < -0.2$
- $-0.2 \leq x < 0$
- $0 \leq x < 0.2$
- $0.2 \leq x < 0.4$
- $0.4 \leq x < 0.6$
- $0.6 \leq x < 0.8$
- $x \geq 0.8$
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?

- 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.

ME (Middle East); CAs (Central Asia); WAf (West Africa); WNA (Western North America); EAf (East Africa); SAm (South America); EU (Europe); CAm (Central America); ENA (Eastern North America); EAs (Eastern Asia); ANZ (Australia/New Zealand)
Incorporating Urban Areas into CLM
Community Land Model Urban

Atmospheric Forcing

- $T_{atm}, q_{atm}$
- $P_{atm}, S_{atm}, L_{atm}$

Canopy Air Space

- $T_s, q_s, u_s$

Floor

- $T_{min} < T_{i,B} < T_{max}$
- Conduction
- Convection
- Radiation
- Ventilation

Impervious

- $R_{imprvrd}$

Pervious

- $R_{prvrd}$

Shaded Wall

- $H_{shdwall}$

Sunlit Wall

- $H_{sunwall}$

Roof

- $H_{roof}$
- $E_{roof}$

Waste

- $H_{waste}$

Imprvrd Wall

- $H_{imprvrd}$
- $E_{imprvrd}$

Prvrd Wall

- $H_{prvrd}$
- $E_{prvrd}$
Urban properties

Tall Building District

Built-up roof of asphalt-based materials (e.g., felt, bitumen) over insulated cellular concrete deck.

$19^\circ C < T_{i,B} < 27^\circ C$


Concrete over soil

$1 - f_{perv} = 0.87$

$f_{perv} = 0.13$

W = 25 m; H/W = 4

$f_{\text{roof}} = 0.6$

Global
Canyon H/W

Pervious Fraction

H = 100 m
## Urban Density Classes

<table>
<thead>
<tr>
<th>Urban Class</th>
<th>H/W</th>
<th>Building Heights (m)</th>
<th>Pervious Fraction (%)</th>
<th>Population Density (km²)</th>
<th>Typical Building Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tall Building District (TBD)</td>
<td>4.6</td>
<td>40-200+</td>
<td>5-15</td>
<td>14,000 - 134,000+</td>
<td>Skyscrapers</td>
</tr>
<tr>
<td>High Density (HD) Residential/ Commercial/ Industrial</td>
<td>1.6</td>
<td>17-45</td>
<td>15-30</td>
<td>5,000 - 80,000+</td>
<td>Tall apartments, office bldgs, industry</td>
</tr>
<tr>
<td>Medium Density (MD) Residential</td>
<td>0.7</td>
<td>8-17</td>
<td>20-60</td>
<td>1,000 - 7,000</td>
<td>1-3 story apartment bldgs, row houses</td>
</tr>
</tbody>
</table>
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:

\[
\frac{H}{W} = 3 \quad \text{vs.} \quad \frac{H}{W} = 3 \\
f_{\text{pervious}} = 0.8 \quad f_{\text{pervious}} = 0
\]

• 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

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

- Canyon air temperature
- Roof surface temperature
- Wall surface temperature
- Road surface temperature
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)
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, savannas, and shrublands
DE – Desert and xeric shrublands
MS – Mediterranean forests, woodlands, shrub (California)
GS – Temperate grasslands, savannas, and shrublands (Texas)
GT – Tropical and subtropical grasslands, savannas, 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

<table>
<thead>
<tr>
<th>Biome</th>
<th>Summer Day</th>
<th>Summer Night</th>
<th>Winter Day</th>
<th>Winter Night</th>
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<tbody>
<tr>
<td>FE</td>
<td>5.7</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FA</td>
<td>5.3</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GN</td>
<td>4.7</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DE</td>
<td>4.3</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS</td>
<td>4.7/4.8</td>
<td>2.8/1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GS</td>
<td>3.6</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GT</td>
<td>3.6</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW</td>
<td>3.6</td>
<td>2.2</td>
<td></td>
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CLMU Daily Average Surface UHI (°C)

<table>
<thead>
<tr>
<th>Surface Type</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>NET</td>
<td>5.7</td>
<td>2.1</td>
</tr>
<tr>
<td>BDT</td>
<td>5.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Crop</td>
<td>4.7</td>
<td>2.8</td>
</tr>
<tr>
<td>C3/C4 Grass</td>
<td>4.7/4.8</td>
<td>2.8/1.6</td>
</tr>
<tr>
<td>Bare Ground</td>
<td>4.3</td>
<td>3.2</td>
</tr>
<tr>
<td>BDS</td>
<td>3.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>OBS</th>
<th>Model</th>
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<tr>
<td>Day</td>
<td>0.58</td>
<td>0.55</td>
</tr>
<tr>
<td>Night</td>
<td>1.22</td>
<td>1.25</td>
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<table>
<thead>
<tr>
<th></th>
<th>OBS</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>0.38</td>
<td>0.32</td>
</tr>
<tr>
<td>Night</td>
<td>1.17</td>
<td>1.39</td>
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</table>
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)

<table>
<thead>
<tr>
<th></th>
<th>JACK_MD</th>
<th>JACK_HD</th>
<th>JACK_TBD</th>
</tr>
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<tbody>
<tr>
<td>DJF</td>
<td>1.4</td>
<td>2.0</td>
<td>4.1</td>
</tr>
<tr>
<td>JJA</td>
<td>1.2</td>
<td>1.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Present-day (PD) and Mid-century (MC) High Heat Stress Days and Nights

Number of days per summer with HImin and HImax exceeding the PD RURAL HImin95 and HImax95

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 HImin above 30°C and 12 days with HImax 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 HImax above 38°C and 54 nights above 30°C; urban Houston has 77 days with HImax above 38°C and 76 nights with HImin above 30°C).

<table>
<thead>
<tr>
<th></th>
<th>HImax95 [°C(F)]</th>
<th>HImin95 [°C(F)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix</td>
<td>42 (108)</td>
<td>30 (86)</td>
</tr>
<tr>
<td>Houston</td>
<td>38 (100)</td>
<td>30 (86)</td>
</tr>
</tbody>
</table>

Oleson et al. 2013, Climatic Change
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

Experiment Results

ALB — CON Urban Heat Island (°C)

- Large Roof Fraction
- Large ALB-CON Roof Albedo
Experiment Results

ALB — CON Urban Heat Island (°C)

- Low incoming solar
- Snow
- Increased space heating
- Slightly cooler climate in the ALB simulation

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

Effects of white roofs:
- Reduce daytime available energy and sensible heat
- Cools daytime temperatures more than nighttime temperatures
- Cooler daily mean temperature (-0.5°C)
Mitigation – White Roofs

JJA average diurnal cycle
40.7N, 287.5E

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)

Oleson et al. 2010, GRL.
Model Evaluation - Anthropogenic Heat Flux

CLMU Building Energy Model

Conduction
Convection
Radiation
Ventilation

Year 2005 Anthropogenic Heat Flux (W m⁻²)
CLMU V2

Flanner et al. 2009 (adjusted)

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

<table>
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<th>Estimated (IEA and UNEP)</th>
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Note: CLMU Version 2.0
Effects of Urban Density and AHF on UHI

CLM forced by NLDAS (1990-2009)

Average Urban – Rural MIN Air Temp (°C)

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<th>VANC_HAC</th>
<th>VANC_HACWST</th>
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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)