Urbanizing the Community Earth System Model (CESM): Overview and Applications

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Global climate change simulations until recently have failed to account for urban areas, which is where the majority of people live.

“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 warming as well as how climate change and urban areas might interact.
Outline

• Community Land Model Urban (CLMU) – Overview
• Application – Urban heat island mitigation
• Application – Contrasts between urban and rural climate in CESM CMIP5 AR5 climate change scenarios
• Future work
Urban Areas in CESM

Gridcell

Landunits:
- Glacier
- Wetland
- Urban
- Lake
- Vegetated

Columns:
- Roof
- Sunlit Wall
- Shaded Wall
- Pervious
- Impervious

Canyon Floor
Community Land Model – Urban (CLMU)

Oleson et al. 2008a, b, JAMC
Urban Input Data

Global Regions

Jackson et al. 2010

Urban Extent - Landscan 2004

Urban Properties – Compilation of building databases

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

Radiative
- Albedo
- Emissivity

Thermal
- Conductivity
- Heat Capacity

Interior temperature settings
Current Global Urban Modeling Capabilities

• Complexity of cities reduced to a single urban landunit
  – Dominant type by area (medium density – from Jackson et al. 2010)
  – 1 to 3 stories, H/W-0.5 to 2.0, significant pervious fraction of canyon floor)

• Coarse spatial resolution
  – Mesoscale features not captured (heat island circulation)
  – Urban and rural areas forced by same climate (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 or global climate

• Degrees of freedom for rural landunit is greater than for urban
  – Rural interacts with atmospheric forcing, plus CO$_2$, nitrogen and aerosol deposition, landcover change (PFTs and LAI).
  – Urban affected only by changes in atmospheric forcing plus interactions of space heating/air conditioning with climate. Urban extent and properties are fixed at present day.
Present Day Urban Energy Balance and Heat Island

Annual Average Diurnal Cycle

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

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

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

Regional Earth System Modeling and Analysis Symposium, Beijing, May 18-21, 2011
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
Urban Design to Mitigate Climate Warming

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

Urban parks

Rooftop gardens

White roofs

Green parking lots
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 and their contribution to the urban heat island?

**CON** – control w/default urban parameter

**ALB** - prescribe global white roof albedo of 0.9.

Urban Heat Island Mitigation - White Roofs

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)

JJA average diurnal cycle 40.7N, 287.5E
Effectiveness of white roofs as a UHI mitigation technique varies according to urban design properties, climate, and interactions with space heating.

Increasing global roof albedo to 0.9 in CLMU reduces annual UHI by 1/3 on average.
Representative Concentration Pathway (RCP)

RCP8.5: High emissions, radiative forcing reaches 8.5 Wm\(^{-2}\) near 2100

RCP4.5: Medium mitigation, radiative forcing stabilizes at \(~4.5\) Wm\(^{-2}\) after 2100

RCP2.6: Stabilization, radiative forcing peaks at 3.1 Wm\(^{-2}\) mid-century, returning to 2.6 Wm\(^{-2}\) by 2100

RCP simulations (5 ensemble members each, 2005-2100) initialized from 20\(^{th}\) century simulations (1850-2005).

Spatial resolution 0.9375°X1.25°
The Urban Heat Island in Perspective

1986-2005 – 1850-1869
Rural climate change

Present day urban heat Island

1986-2005 – 1850-1869
Rural landcover change

Regions from McCarthy et al., 2010
Urban – Rural Daily Maximum Temperature

2080-2099 – 1986-2005

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• Rural EF decreases because of increased water use efficiency by plants due to higher CO₂.
• Urban EF not affected by changes in water use efficiency related to CO₂ and mainly responds to changes in precipitation.
• Rural TMAX warms more than Urban TMAX
2080-2099 – 1986-2005
Urban – Rural Daily Minimum Temperature

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• Changes in rural leaf/stem area control most of the changes in the nocturnal heat island

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<td>$Urban$-$Rural$ $TMIN$</td>
<td>$R = -0.44$</td>
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• Increase in clouds reduces the nocturnal heat island
Summary

Keeping in mind the modeling capabilities discussed earlier:

• Magnitude of present day urban heat island generally comparable to or larger than climate warming from 1850 to present day and much larger than changes in climate due to landcover change.

• Urban and rural areas may respond differently to climate change, e.g.,
  ➢ Urban and rural evaporative fraction (EF) respond differently to climate change which decreases daytime heat island (TMAX)
    – Rural EF lower almost everywhere due to higher water use efficiency under higher CO$_2$, which increases TMAX. Urban EF may increase or decrease mainly in response to changes in P.

  ➢ Significant spatial and temporal variability in changes in nocturnal heat island (TMIN) due to changes in the rural surface and atmospheric forcing
    – For example, in Europe changes in nocturnal heat island due to changes in rural leaf/stem area (in summer) but also by changes in atmospheric forcing (e.g., clouds in winter).

• Argues for explicit modeling of urban areas in climate change simulations
Future Work

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Thank You

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