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

Keith Oleson

NCAR Earth System Laboratory

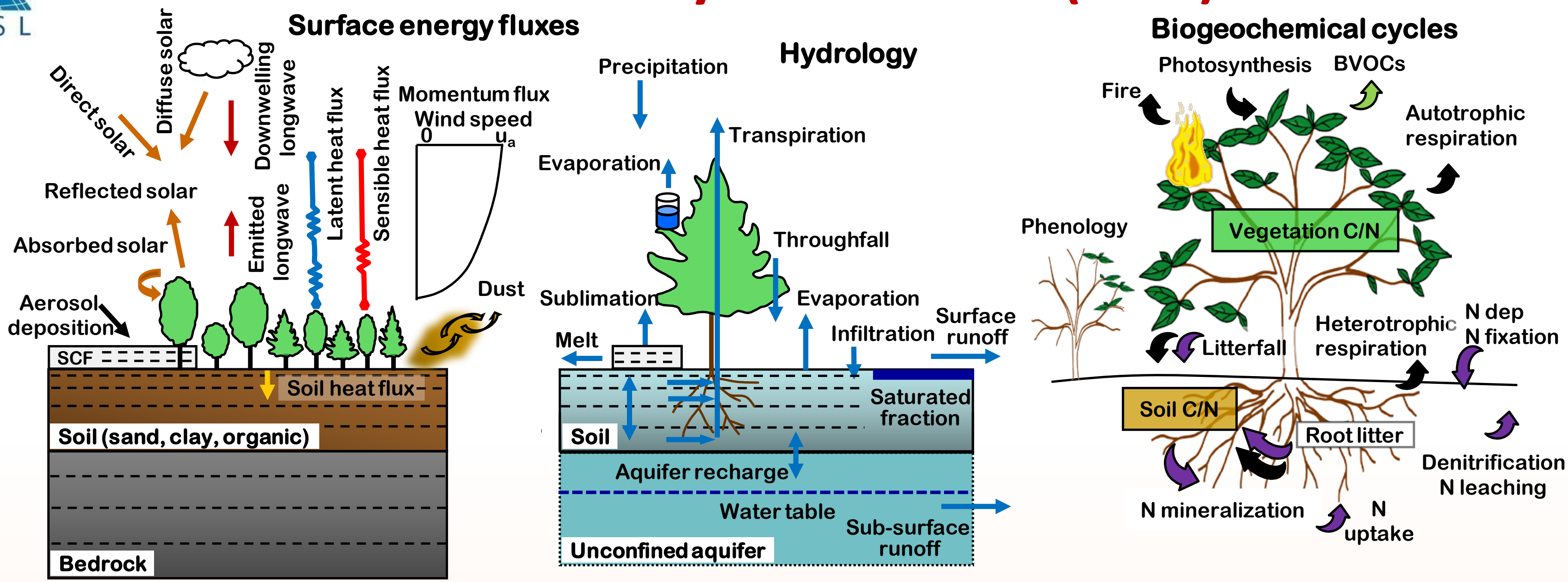
Climate and Global Dynamics Division

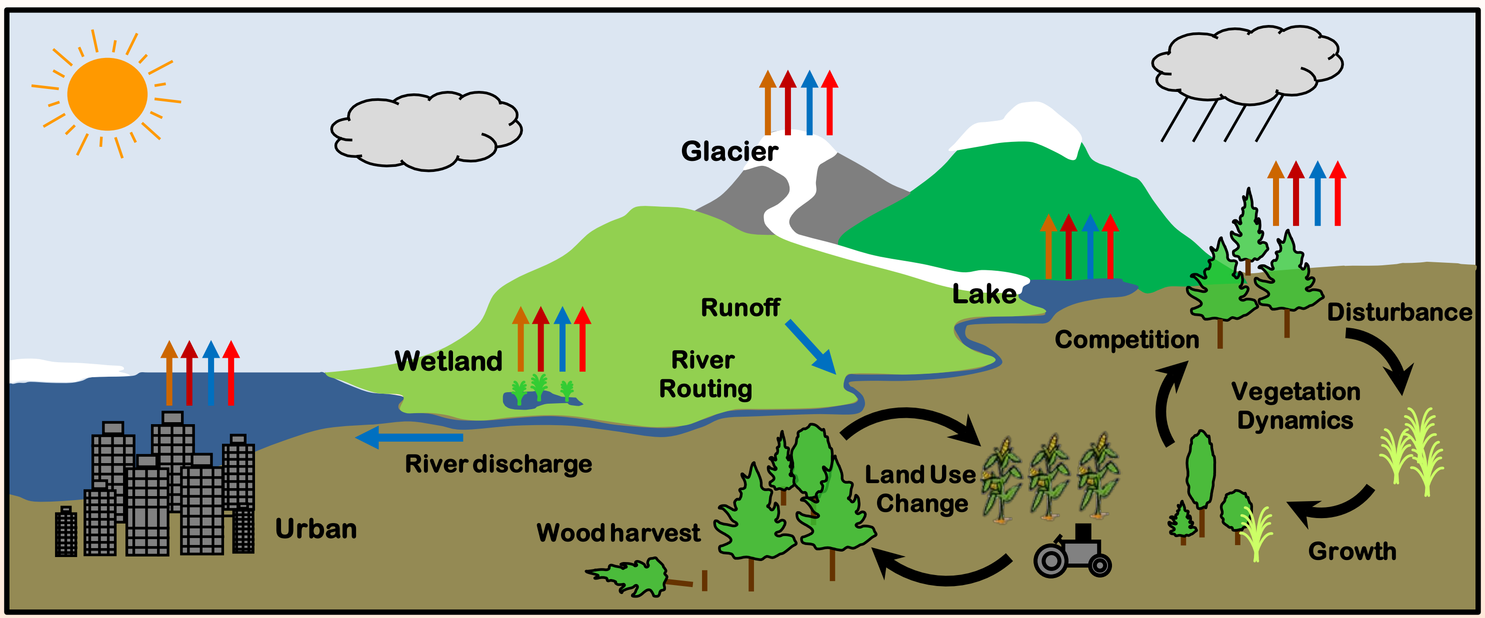
Terrestrial Sciences Section

Collaborators: Gordon Bonan – NCAR, Johannes Feddema– University of Kansas

NCAR is sponsored by the National Science Foundation

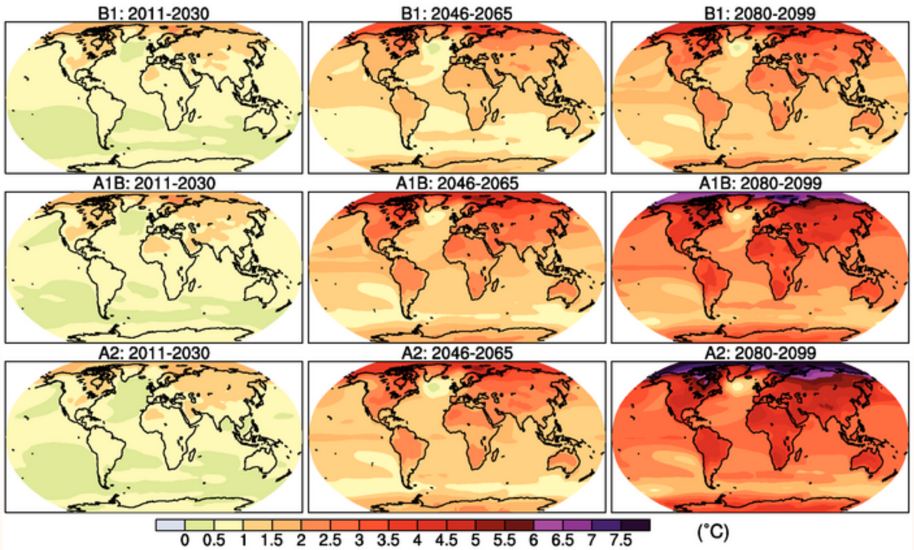
Community Land Model (CLM)



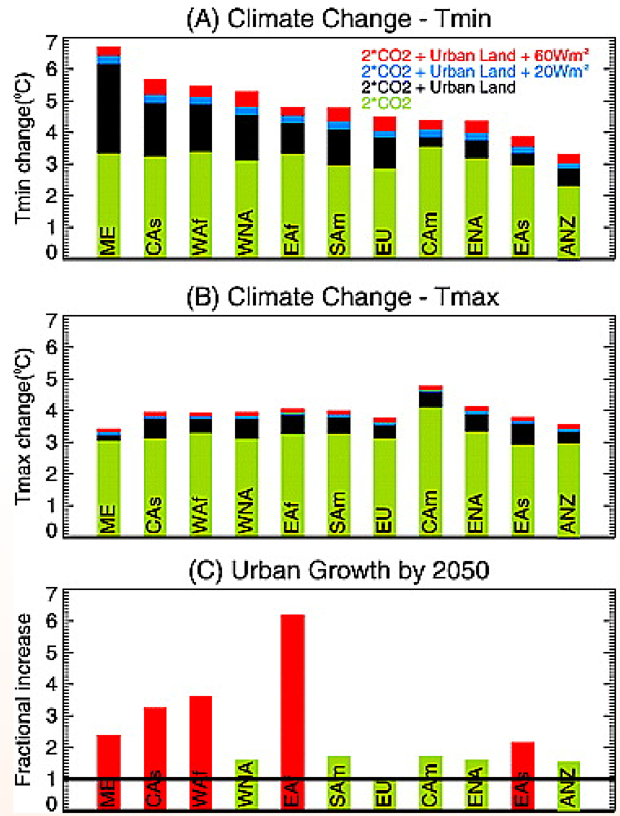


Global Urban Modeling - Motivation

IPCC AR4 multi-model mean of annual mean surface warming



Meehl et al. 2007

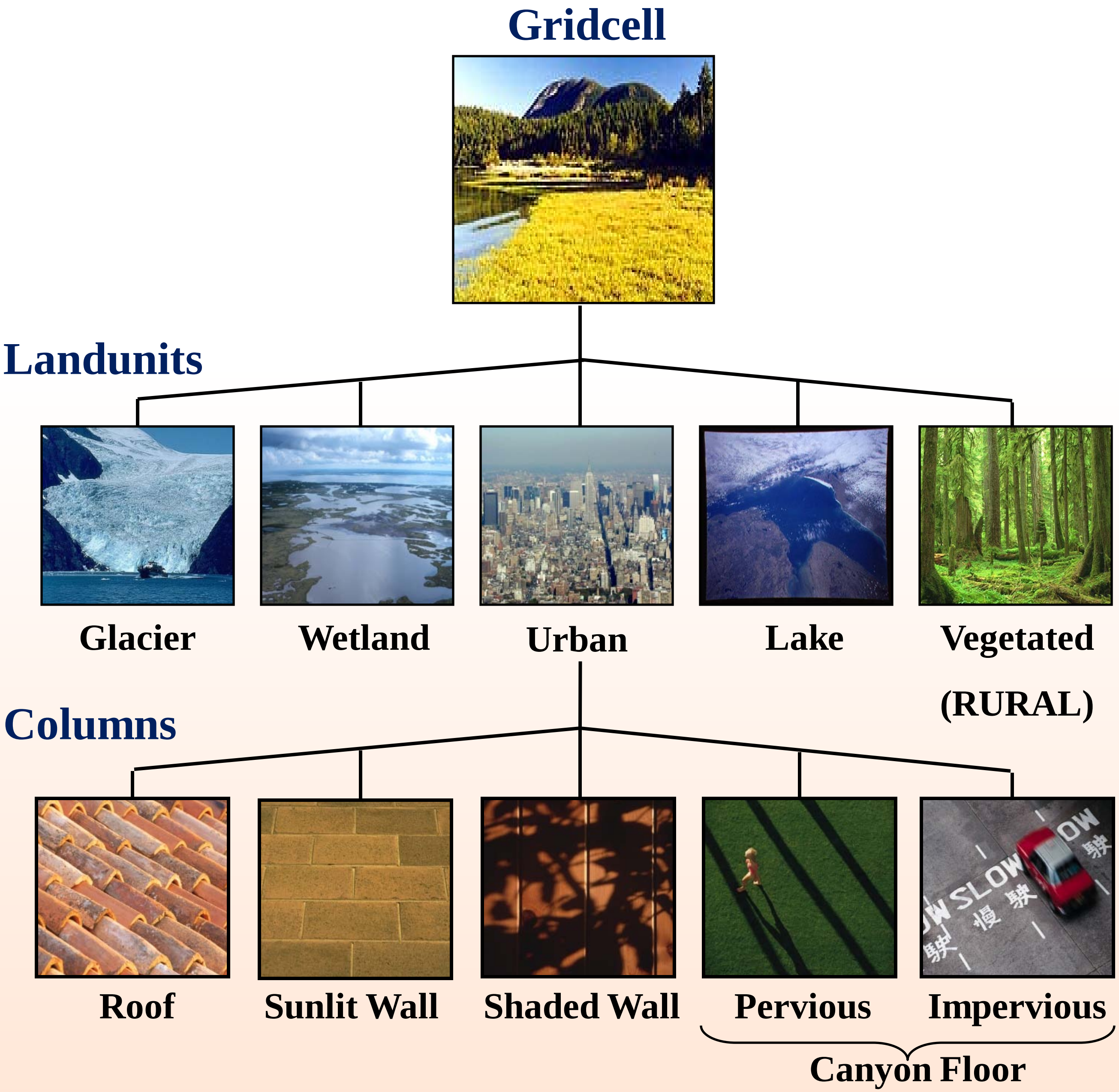


- Global climate change simulations until recently have failed to account for urban areas, which is where the majority of people live.
- “Those regions with the higher cumulative impact of climate change and urban effects are…also projected to at least double their urban populations by 2050” (McCarthy et al. 2010)
- It is important to consider the additional urban warming as well as how climate change and urban areas might interact.

Outline

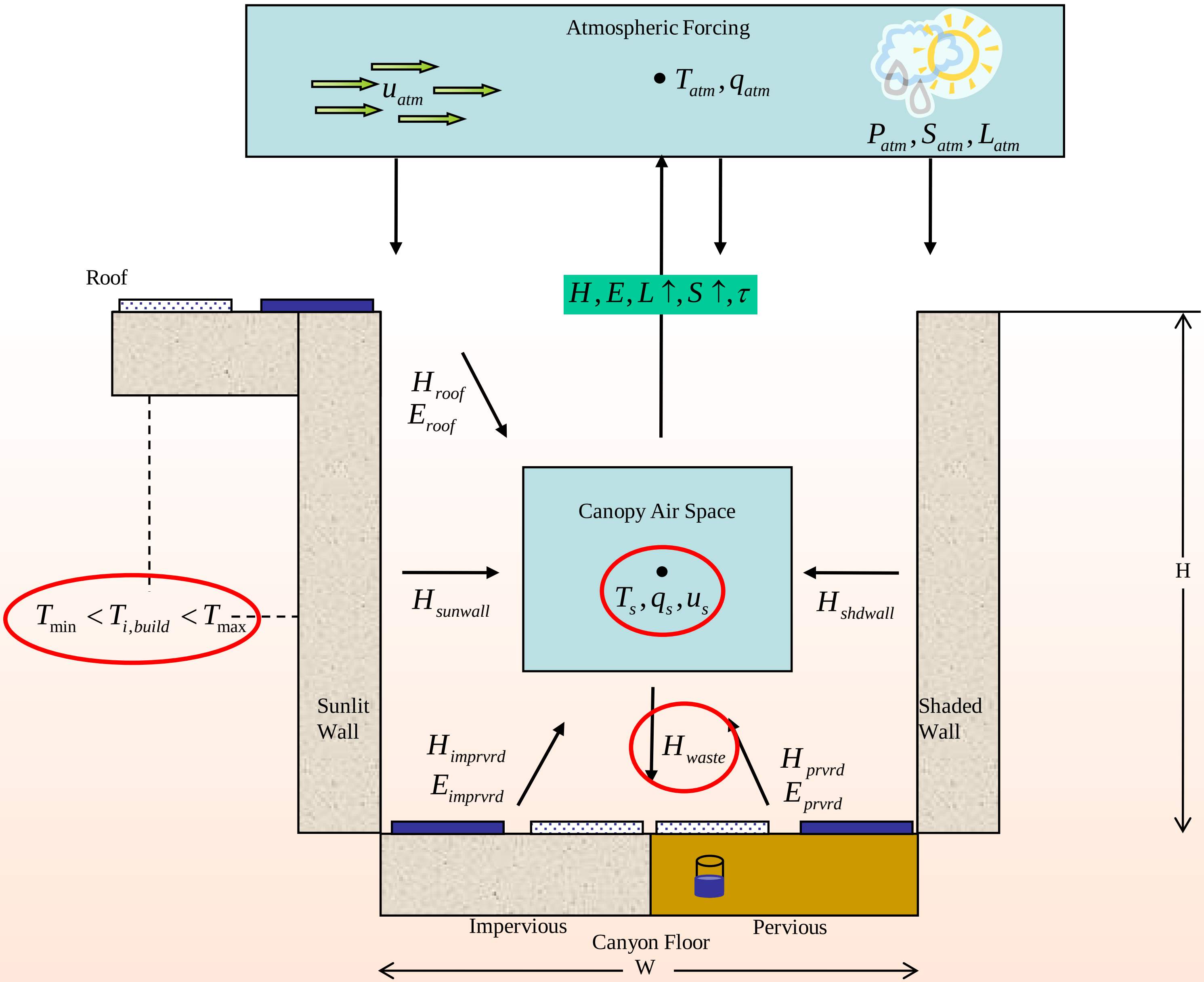
- Community Land Model Urban (CLMU) – Overview
- Application – Urban heat island mitigation
- Application – Contrasts between urban and rural climate in CESM CMIP5 AR5 climate change scenarios
- Future work

Urban Areas in CESM



Community Land Model – Urban (CLMU)

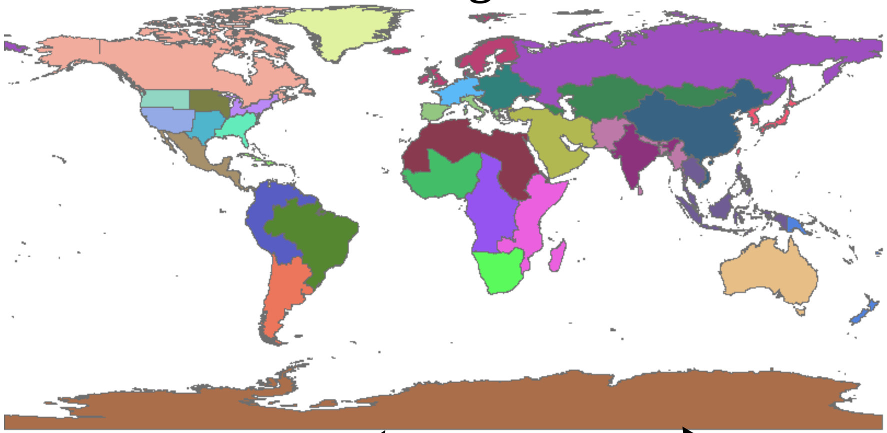
Oleson et al. 2008a, b, *JAMC*



Urban Input Data

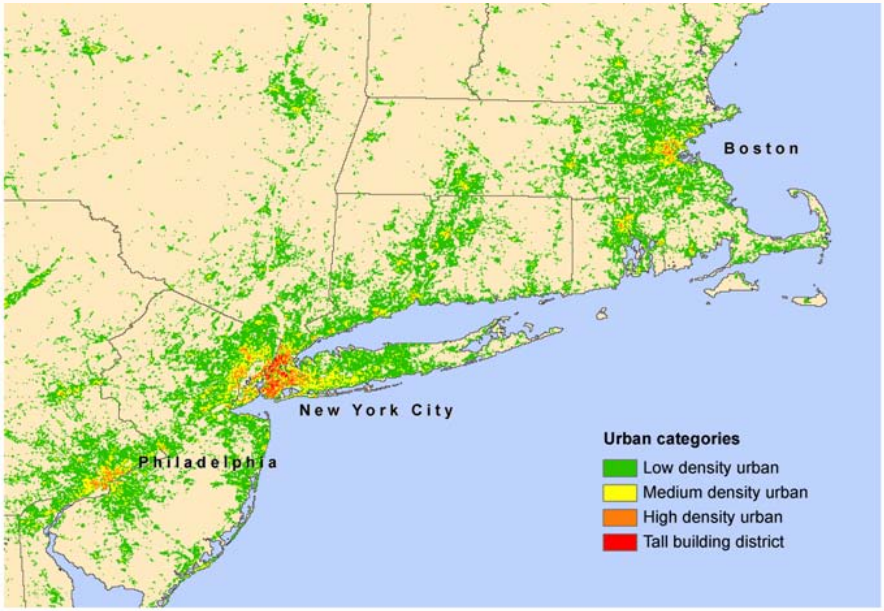
Jackson et al. 2010

Global Regions



To Model

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***

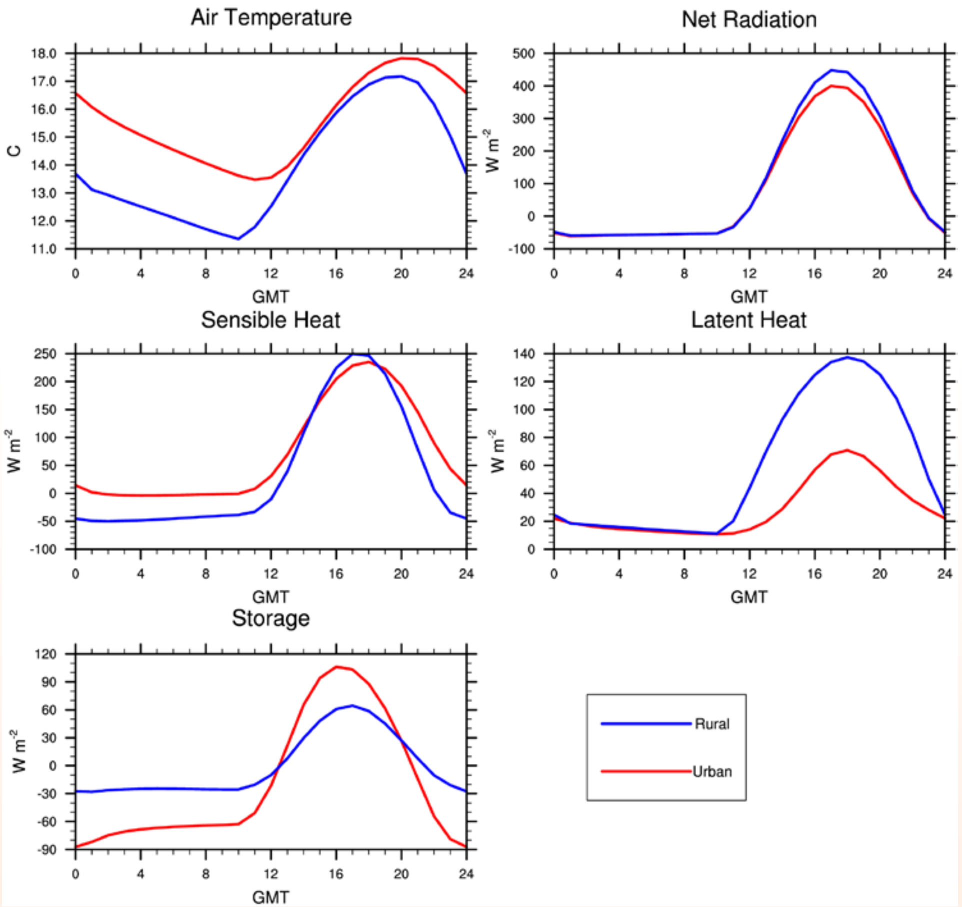
Interior temperature settings

Current Global Urban Modeling Capabilities

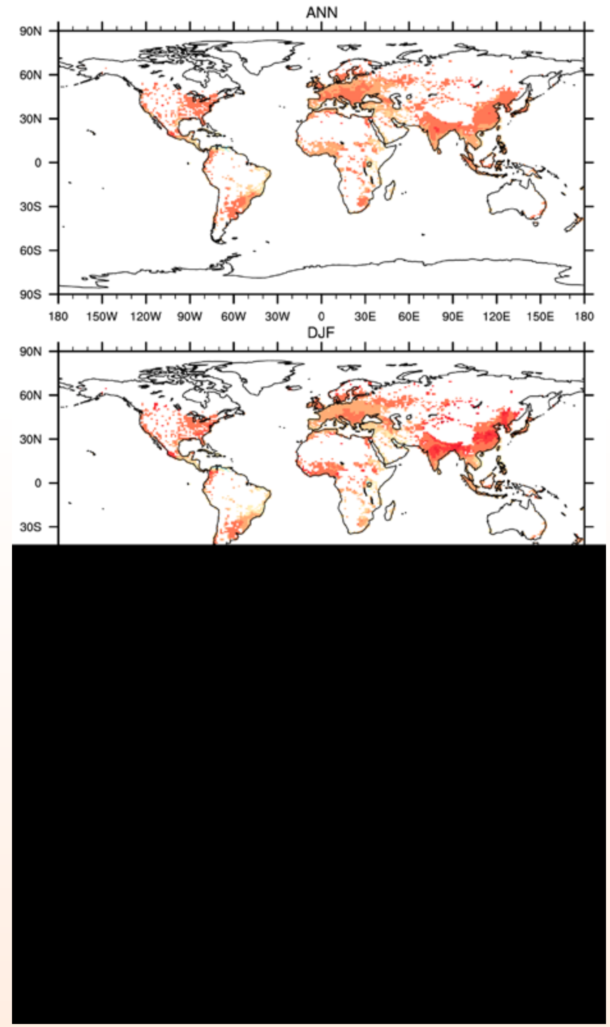
- Complexity of cities reduced to a single urban landunit
  - Dominant type by area (medium density – from Jackson et al. 2010)
  - 1 to 3 stories, H/W-0.5 to 2.0, significant pervious fraction of canyon floor)
- Coarse spatial resolution
  - Mesoscale features not captured (heat island circulation)
  - 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



Heat Island



ANN

DJF

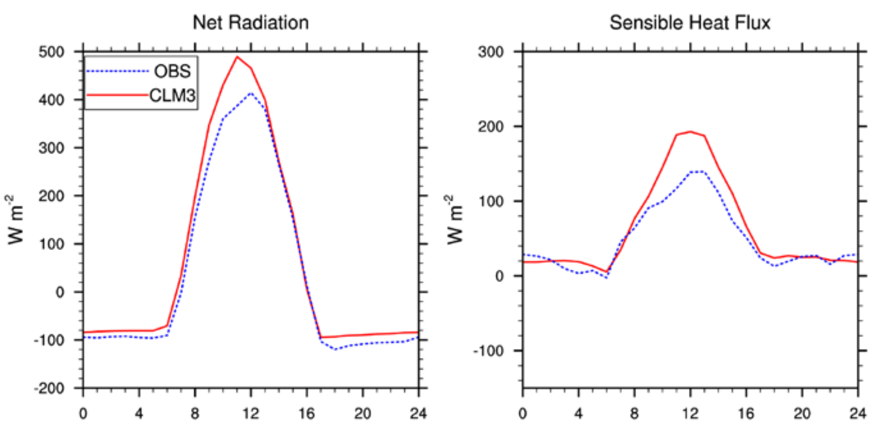
JJA

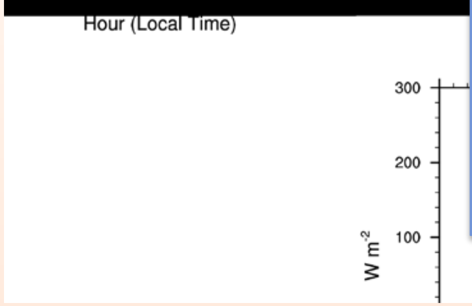
•Urban area stores more heat during daytime and releases heat at night resulting in nighttime heat island

•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

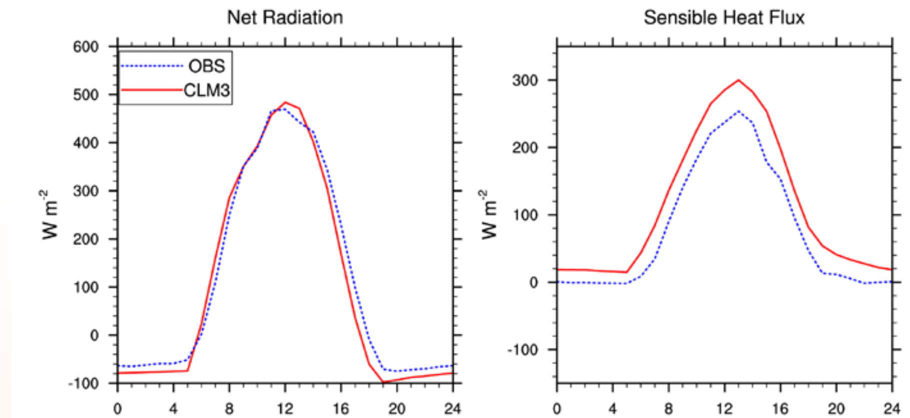
Mexico City – Historic city core
Oke et al. (1999); Dec 2-7, 1993
H/W=1.2, H=18m

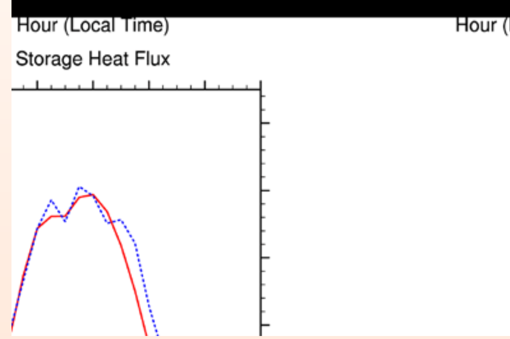




	OBS	Model
Day	0.58	0.55
Night	1.22	1.25

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





	OBS	Model
Day	0.38	0.32
Night	1.17	1.39

Model Evaluation

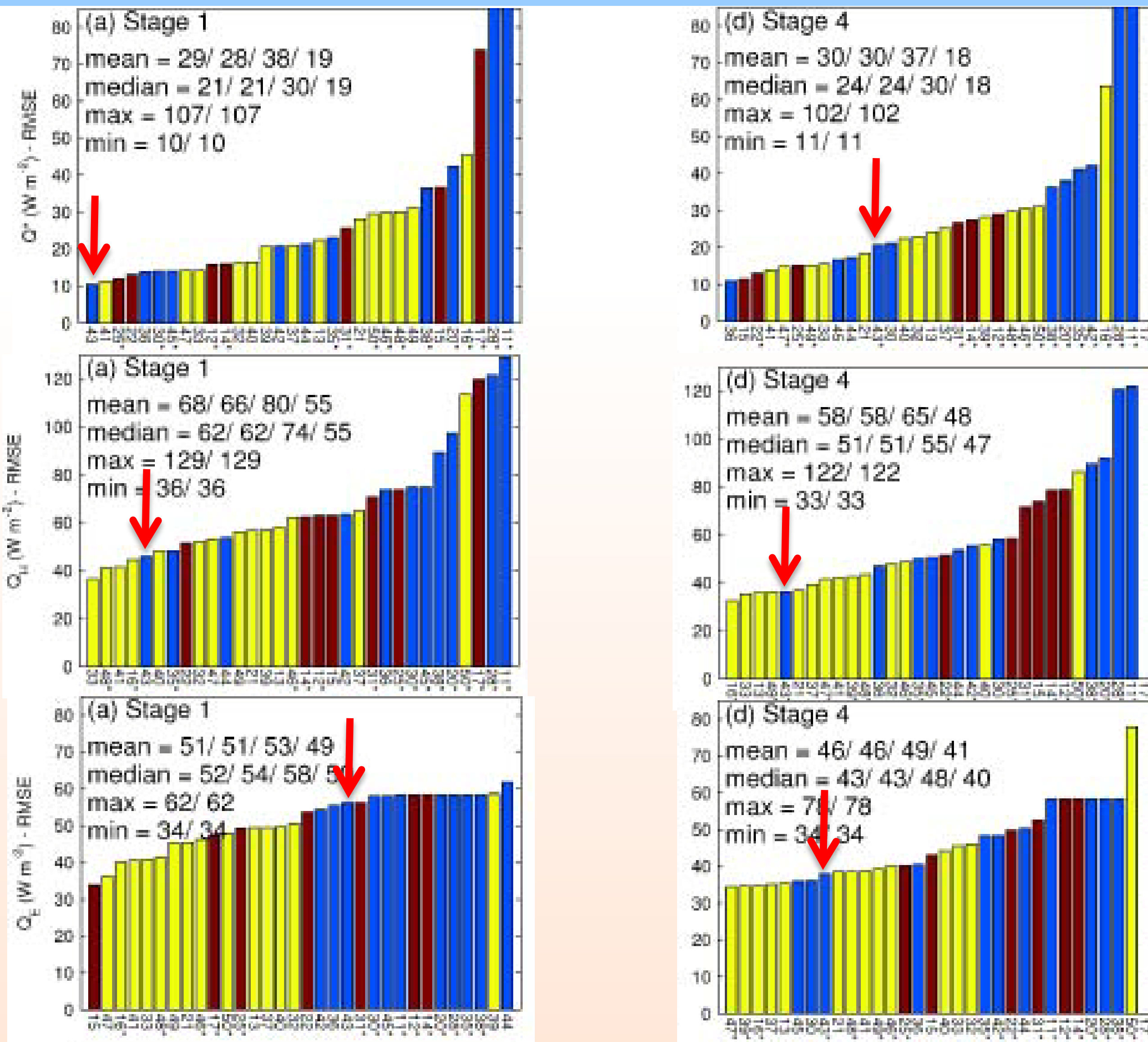
International Urban Energy Balance Model Comparison (Grimmond et al. 2010);

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

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]).

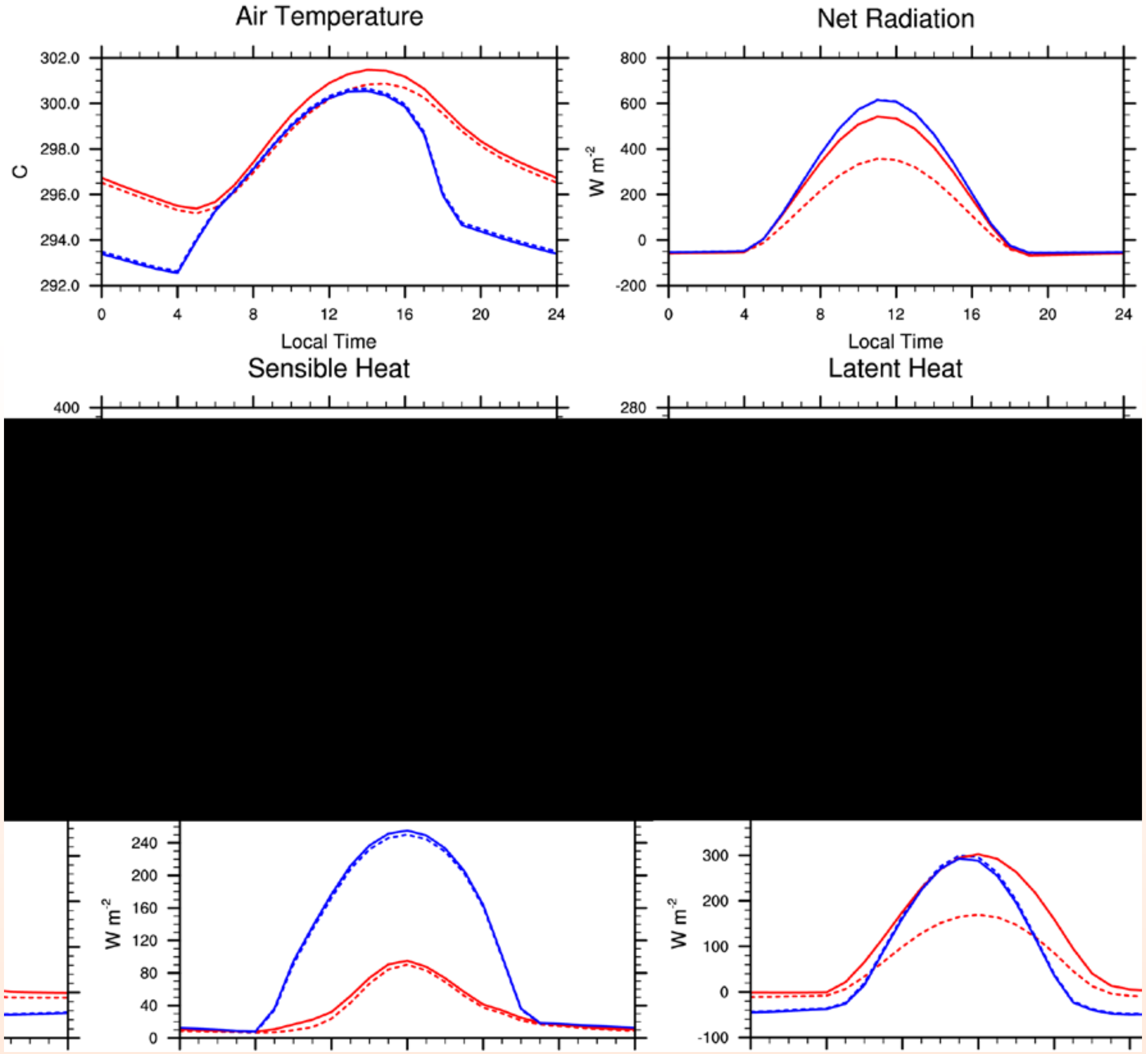
What is the role of roofs in the urban energy budget and their contribution to the urban heat island?

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

JJA average diurnal cycle 40.7N, 287.5E

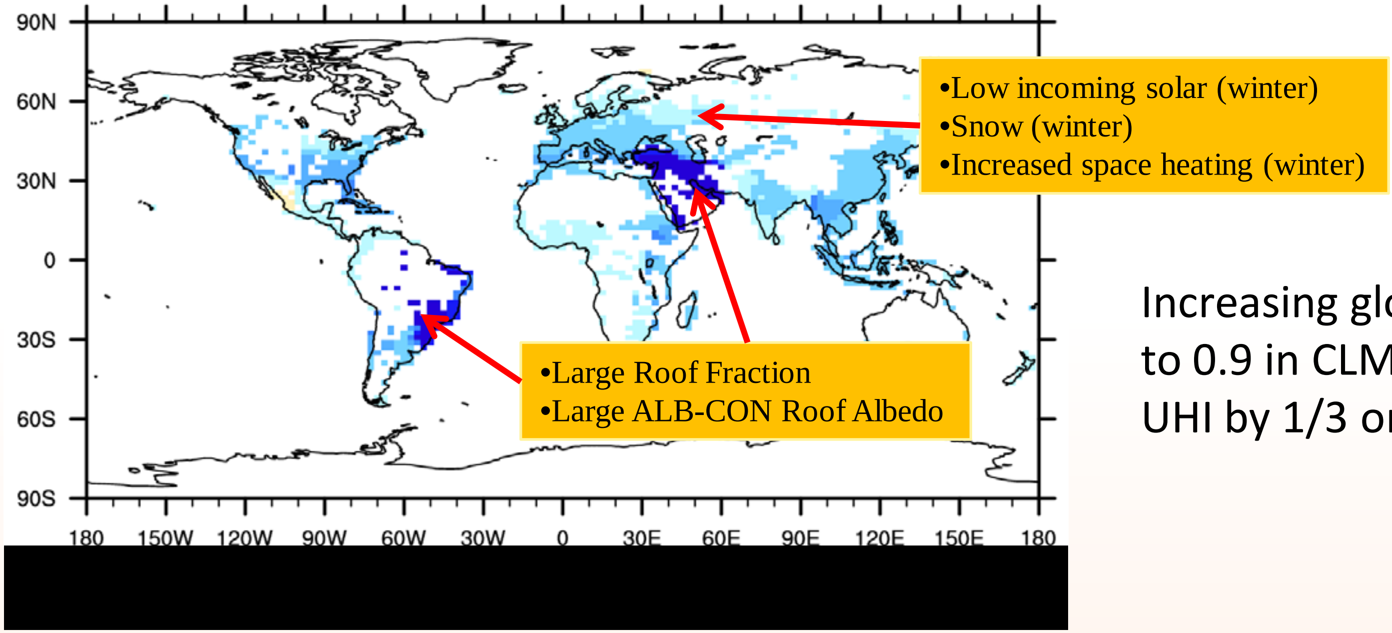


Effects of white roofs:

- Reduce daytime available energy and sensible heat
- Cools daytime temperatures more than nighttime temperatures
- Cooler daily mean temperature (-0.5°C)

Urban Heat Island Mitigation - White Roofs

Reduction in the annual mean Heat Island (°C)

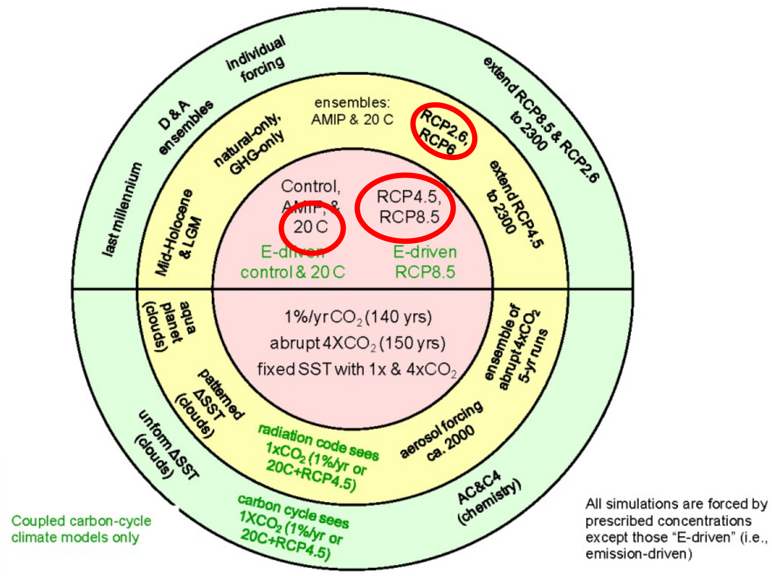


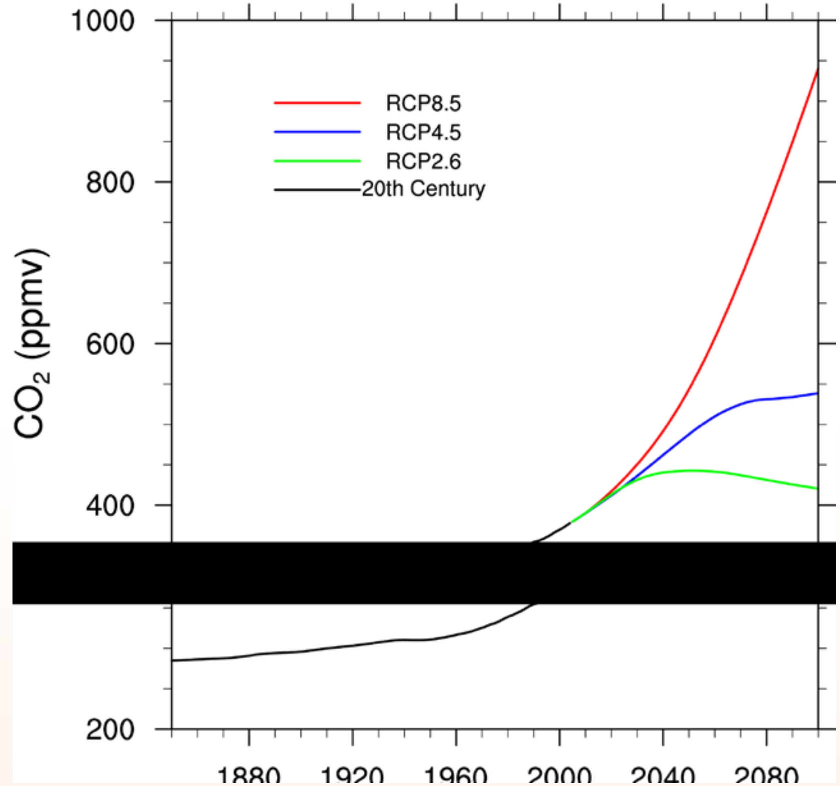
Increasing global roof albedo to 0.9 in CLMU reduces annual UHI by 1/3 on average.

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

Contrasts in response of urban/rural areas to climate change – CESM CMIP5 simulations

Taylor et al. 2009





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 20th century simulations (1850-2005).

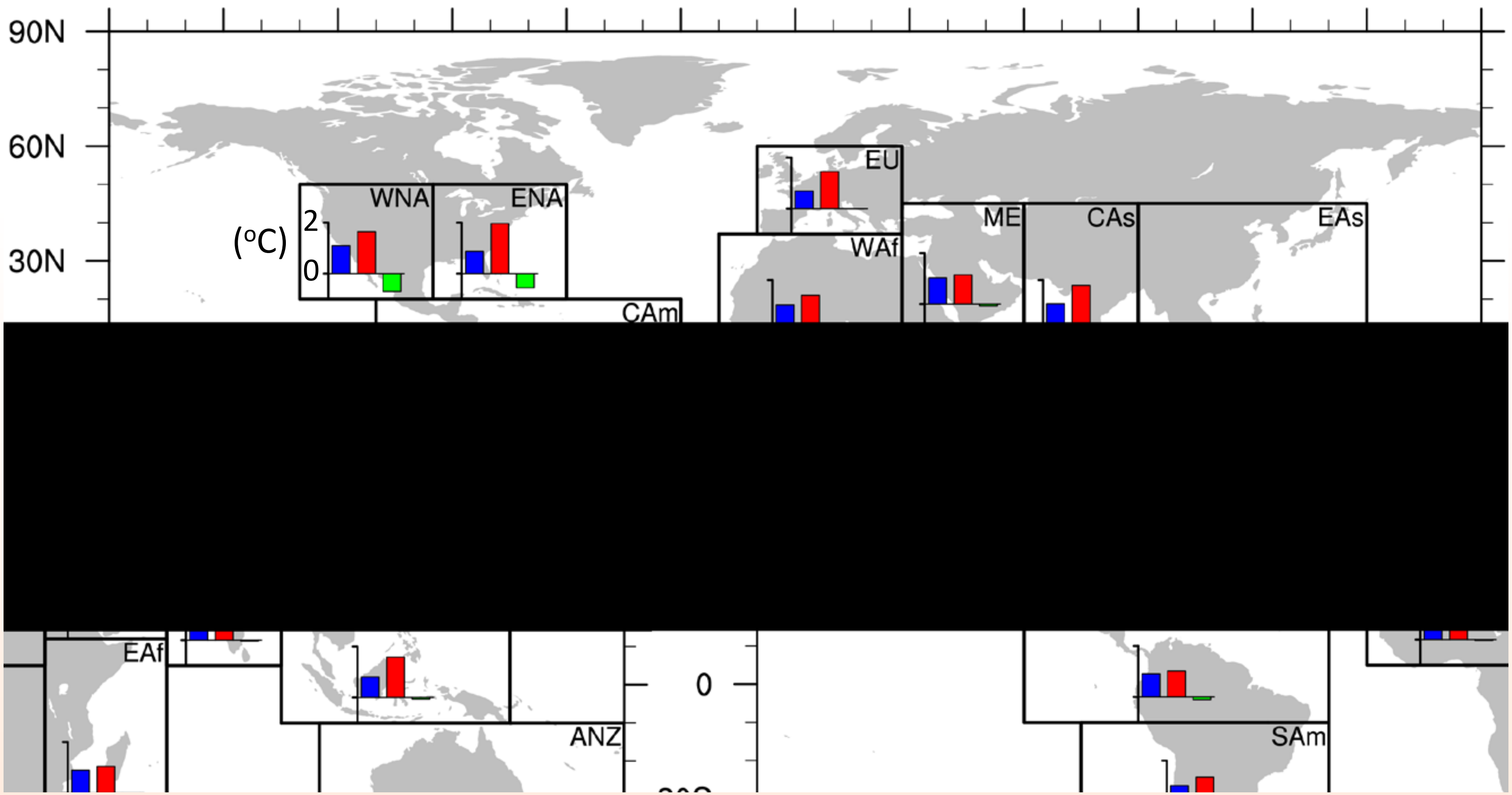
Spatial resolution 0.9375°X1.25°

The Urban Heat Island in Perspective

1986-2005 – 1850-1869
Rural climate change

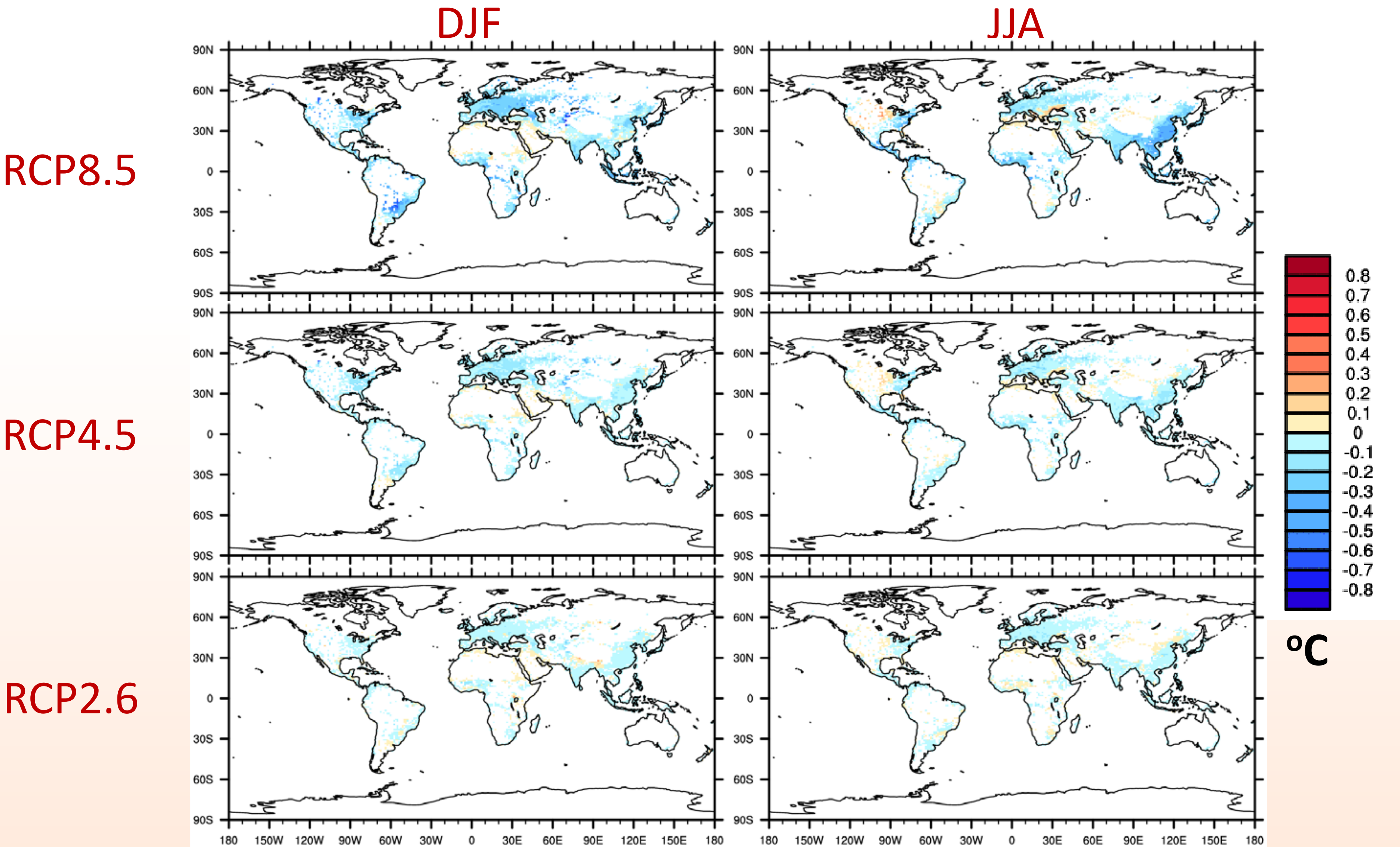
Present day urban
heat Island

1986-2005 – 1850-1869
Rural landcover change



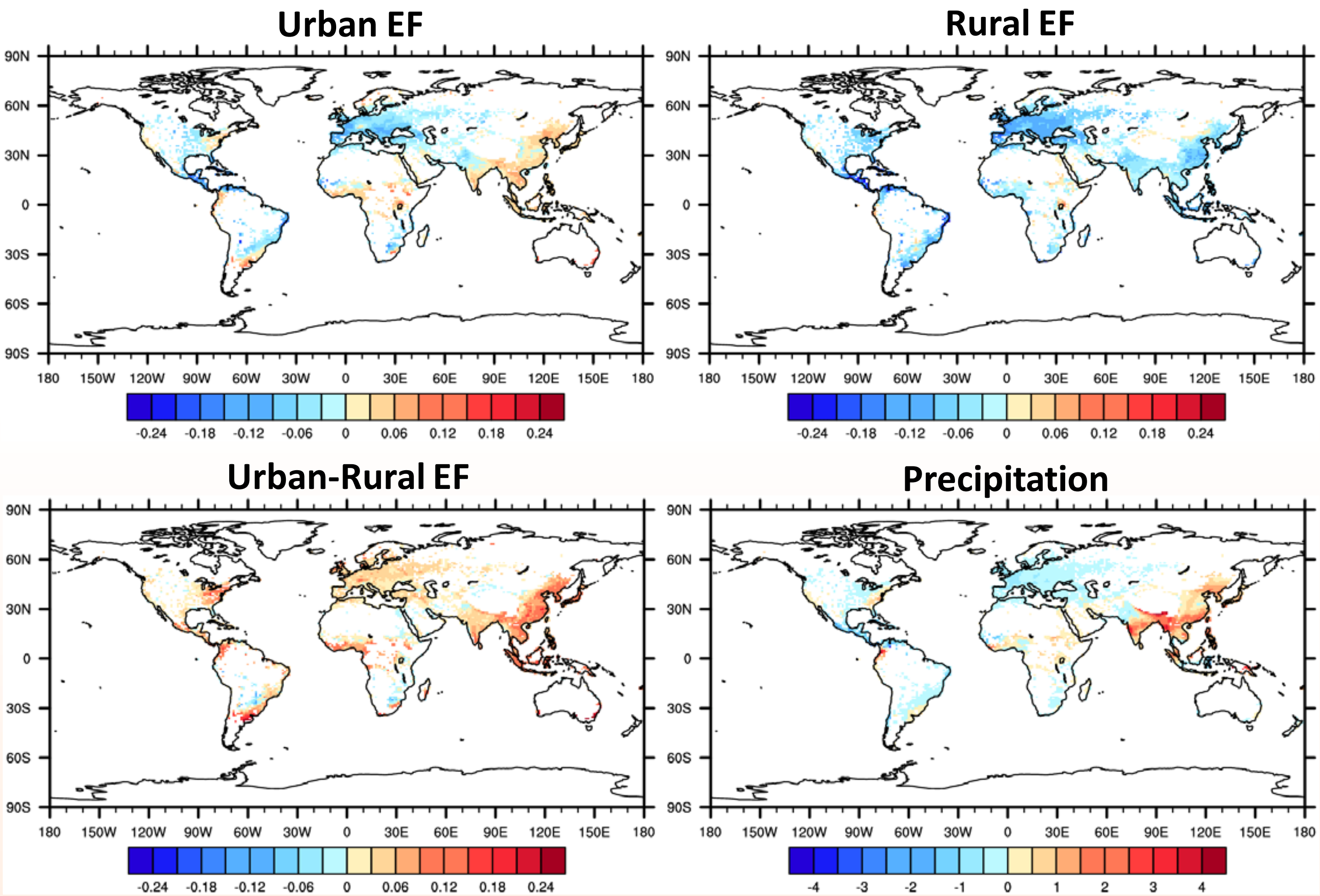
Regions from McCarthy et al., 2010

2080-2099 – 1986-2005
Urban – Rural Daily Maximum Temperature



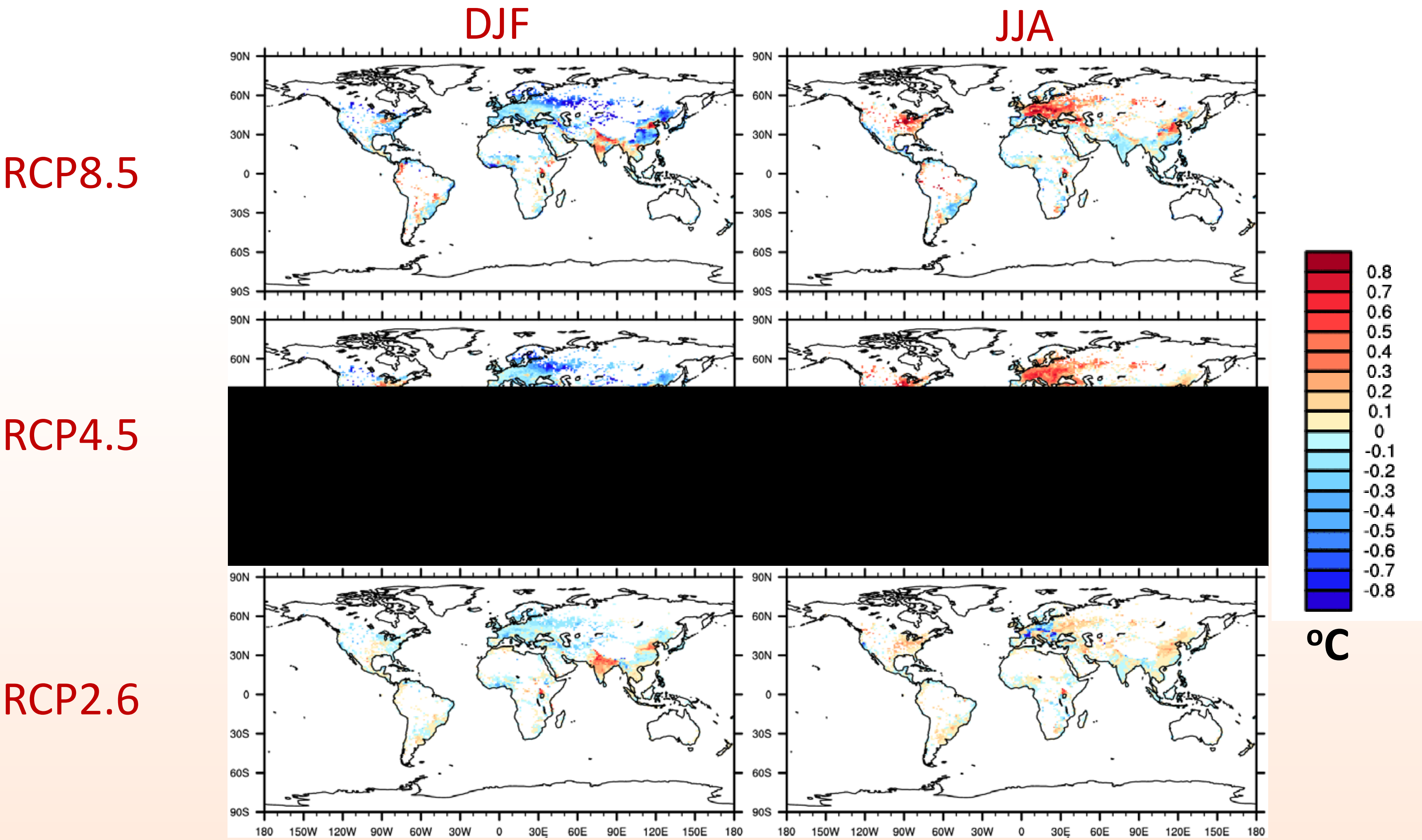
Evaporative Fraction (EF) Effects on TMAX

JJA
RCP8.5

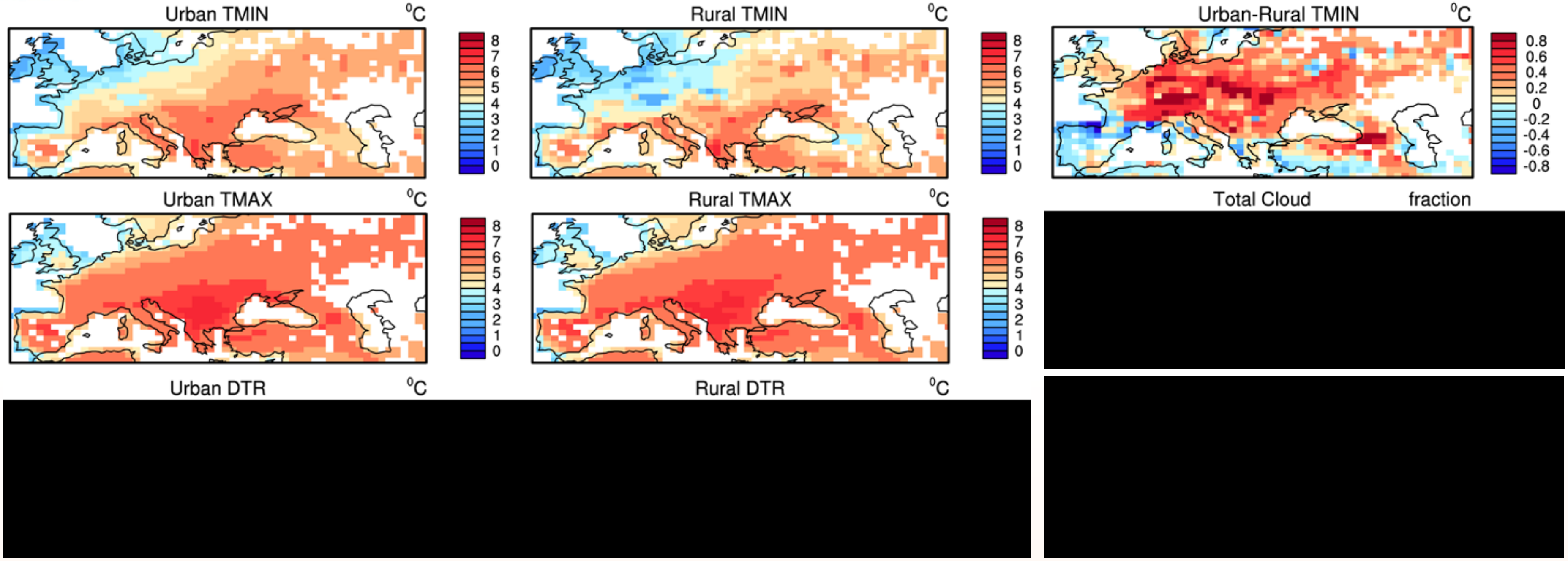


- Rural EF decreases because of increased water use efficiency by plants due to higher CO_2.
- Urban EF not affected by changes in water use efficiency related to CO_2 and mainly responds to changes in precipitation.
- Rural TMAX warms more than Urban TMAX

2080-2099 – 1986-2005
Urban – Rural Daily Minimum Temperature



JJA RCP8.5

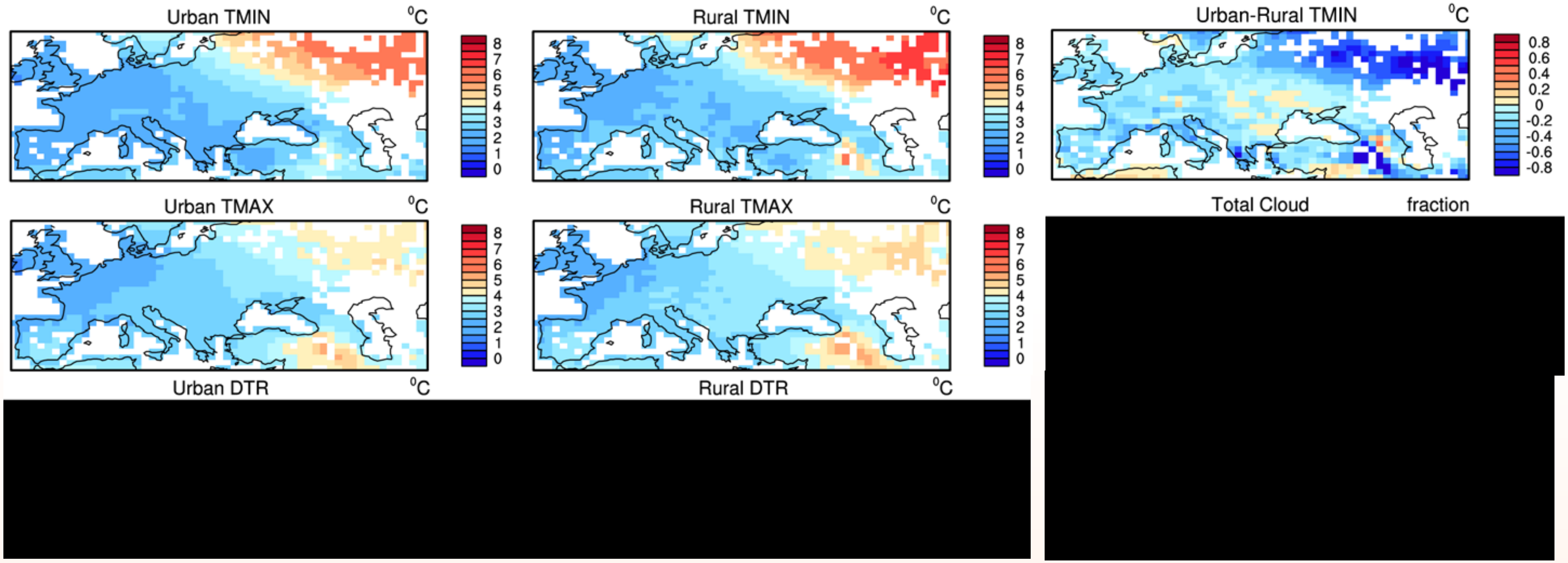


	tc	*lsai*
Urban-Rural TMIN	*R = -0.44*	*R = 0.80*

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

NESL

DJF RCP8.5



[redacted]

	tc	*lw*
Urban TMIN	*R = 0.77*	*0.92*
Rural TMIN	*R = 0.77*	*0.92*

	tc	*lw*
Urban-Rural TMIN	*-0.58*	*-0.66*

- 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

- 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 affected by changes in 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.

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