Climate Simulations with the Urban Model (CLMU)

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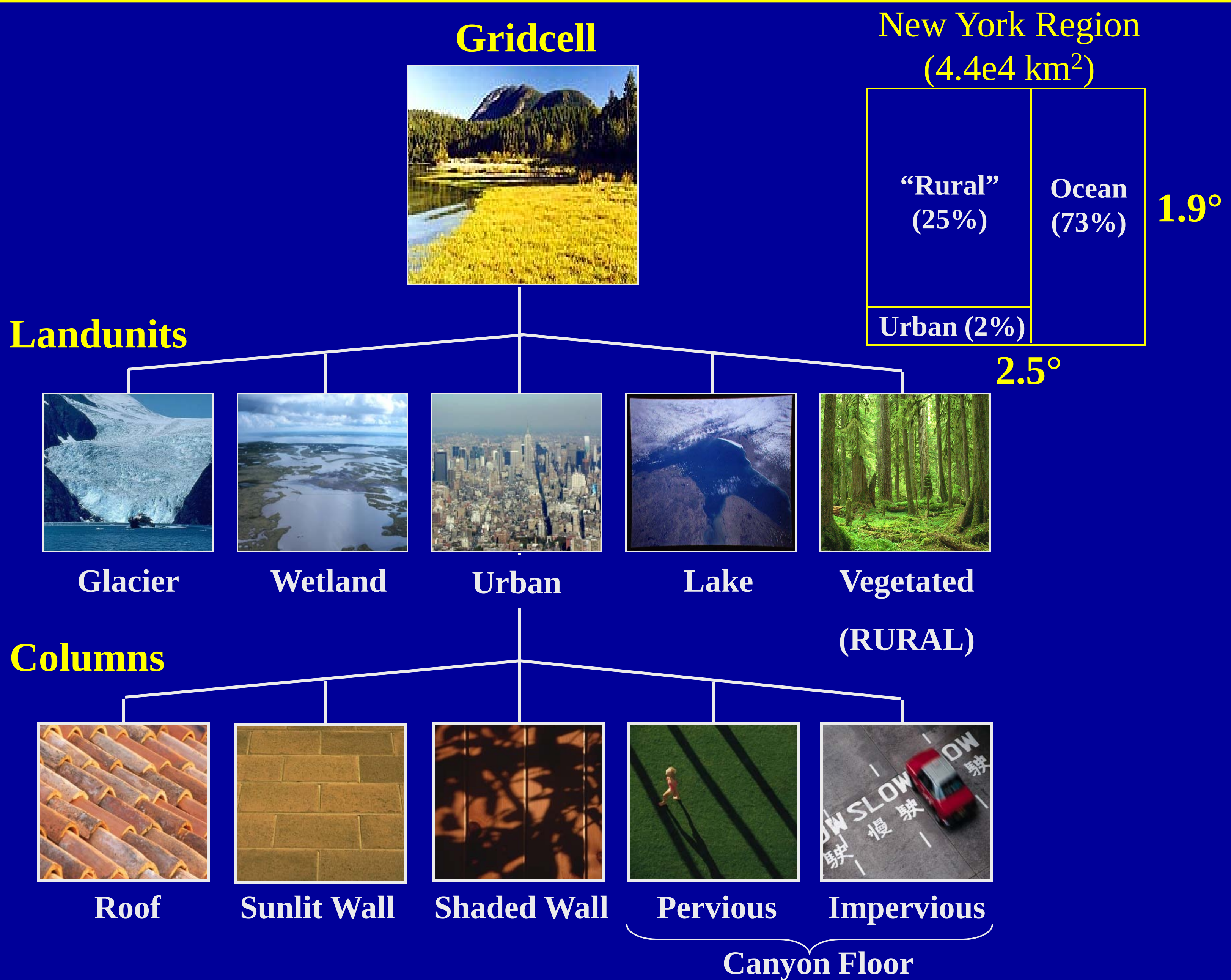
Why urbanize a global climate model?

- Provide climate and climate-change information (e.g., surface air temperature and humidity, surface hydrology, etc.) for urban environments, where the majority of people work and live.

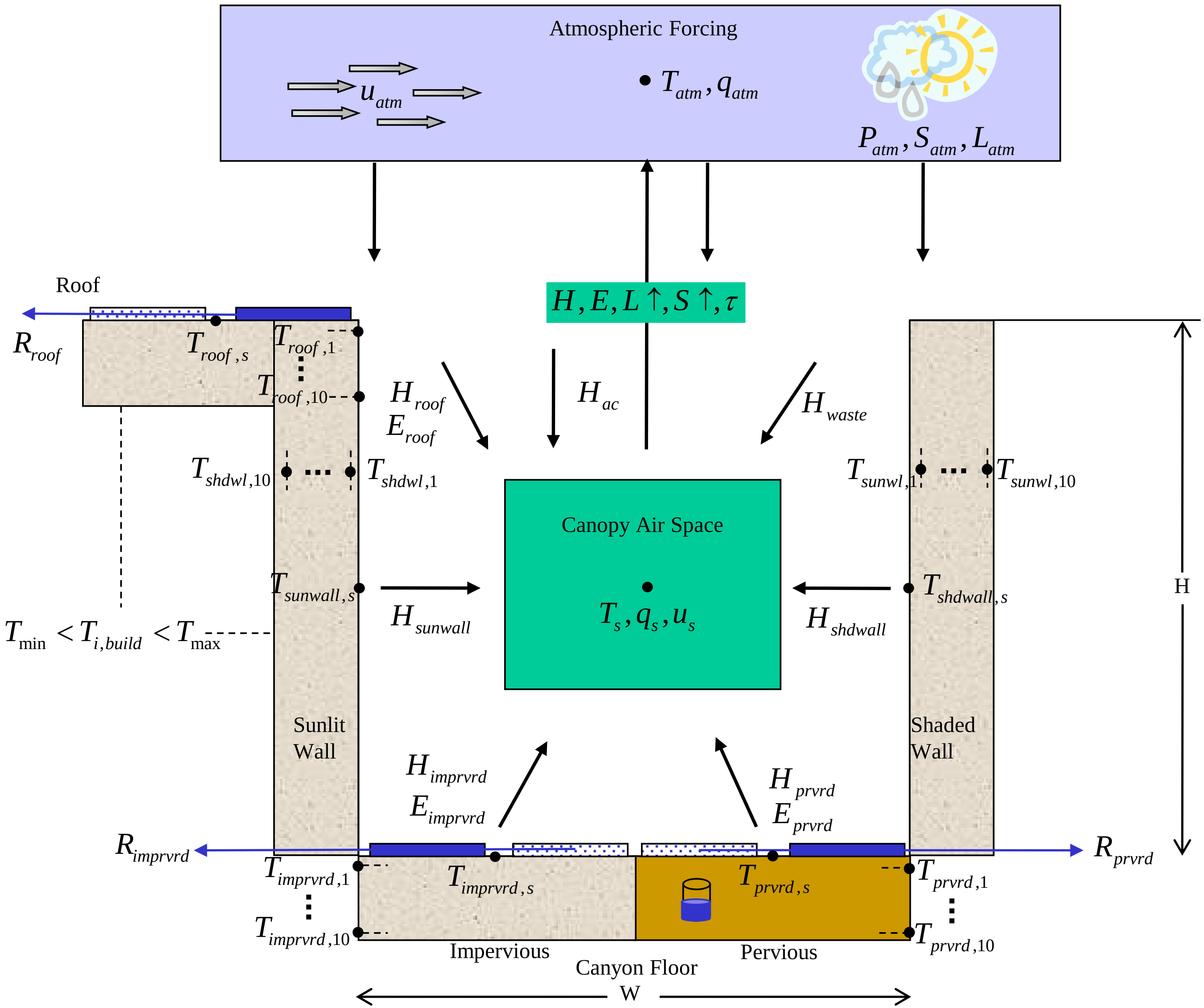
- Assumption of stationarity under radiatively-forced climate change may not be valid for urban heat islands. Heat island characteristics may change as cities evolve. Thus, changes in temperature in urban areas may be more reliably estimated by the explicit modeling of urban heat islands within climate models (Betts and Best 2004).

- Because it's more fun than doing CLM hydrology.

Community Land Model (CLM) Subgrid Structure



CLMU
(Oleson et al. 2008a, 2008b, JAMC)



Urban in CCSM4/CLM4

- Formulation as in Oleson et al. 2008a,b except:
  - Hydrology of pervious canyon floor updated from CLM3.0 to CLM4.0
  - Revised treatment of anthropogenic flux – separate heating and air conditioning (HAC) efficiencies to determine wasteheat, heat removed by air conditioning and wasteheat are put into canyon floor
- Urban active at all resolutions and configurations (e.g., 1850, 2000, transient simulations)
  - No urban landcover change (present day urban similar to lakes, wetlands, glaciers)
  - Prescribed building interior min/max temperatures (HAC), wasteheat flux on

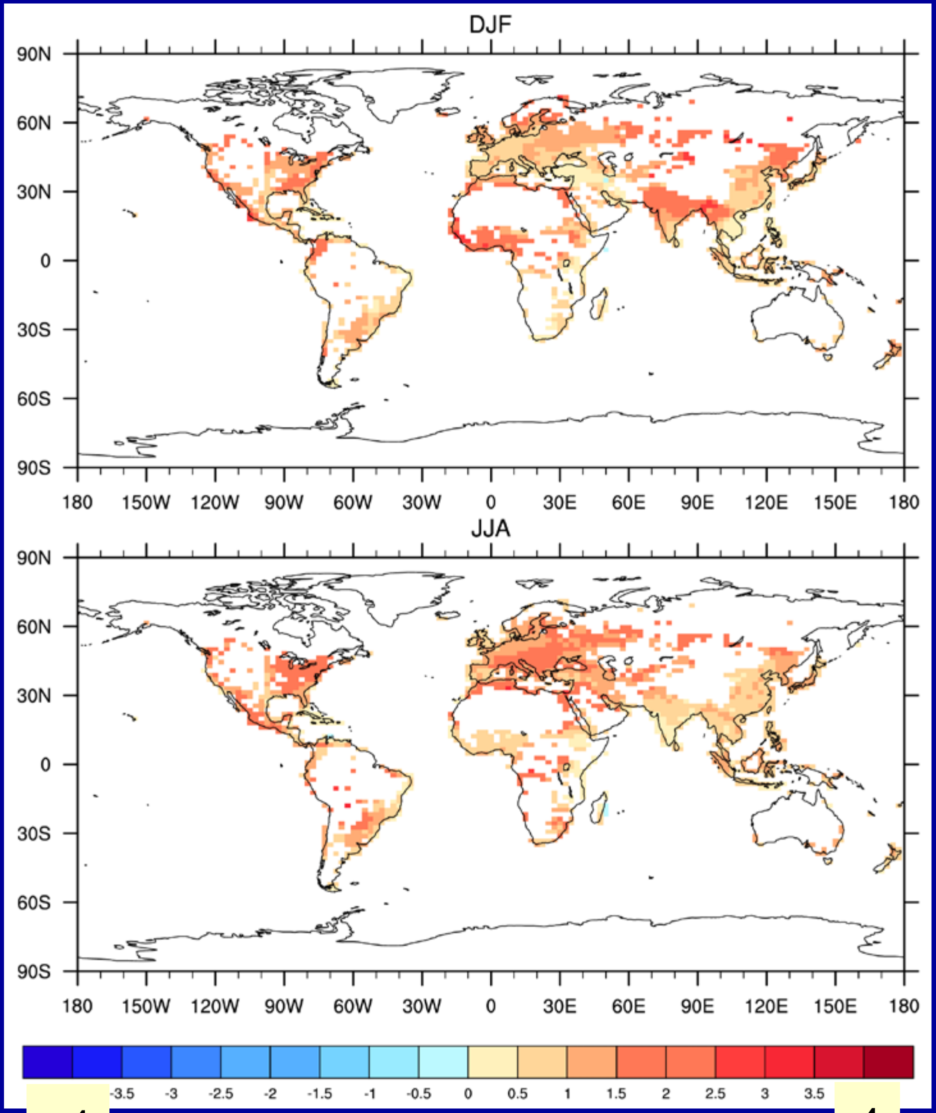
Urban Climate Simulations

- CAM3.5/CLM3.5 – 1.9° X 2.5°
- Prescribed SST, sea-ice and greenhouse gases (CO_2, CH_4, N_2O, CFCs)
  - 1941-1999: AR4 20th century CCSM ensemble member
  - 2000-2099: AR4 A2 scenario CCSM ensemble member
- 1) Prescribed min/max interior building temperatures -NWHF
  2) Inclusion of wasteheat fluxes – WHF

Urban Heat Island Pattern

NWHF

1980-1999 Urban – Rural Surface Air Temperature (C)



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Annual Global (Land Surface) Air Temperature and UHI

(°C) Difference from Base Period (1980-1999)

Simulation	1980-1999	2011-2030	2046-2065	2079-2098
NWHF	-	0.95 (1.17)	1.95 (2.41)	3.40 (4.21)
WHF	-	0.94 (1.11)	1.97 (2.46)	3.41 (4.22)
NWHF UHI	1.12	1.10	1.07	1.03
WHF UHI	1.18	1.15	1.12	1.08
[1]Meehl et al. 2007	-	0.64	1.65	3.13

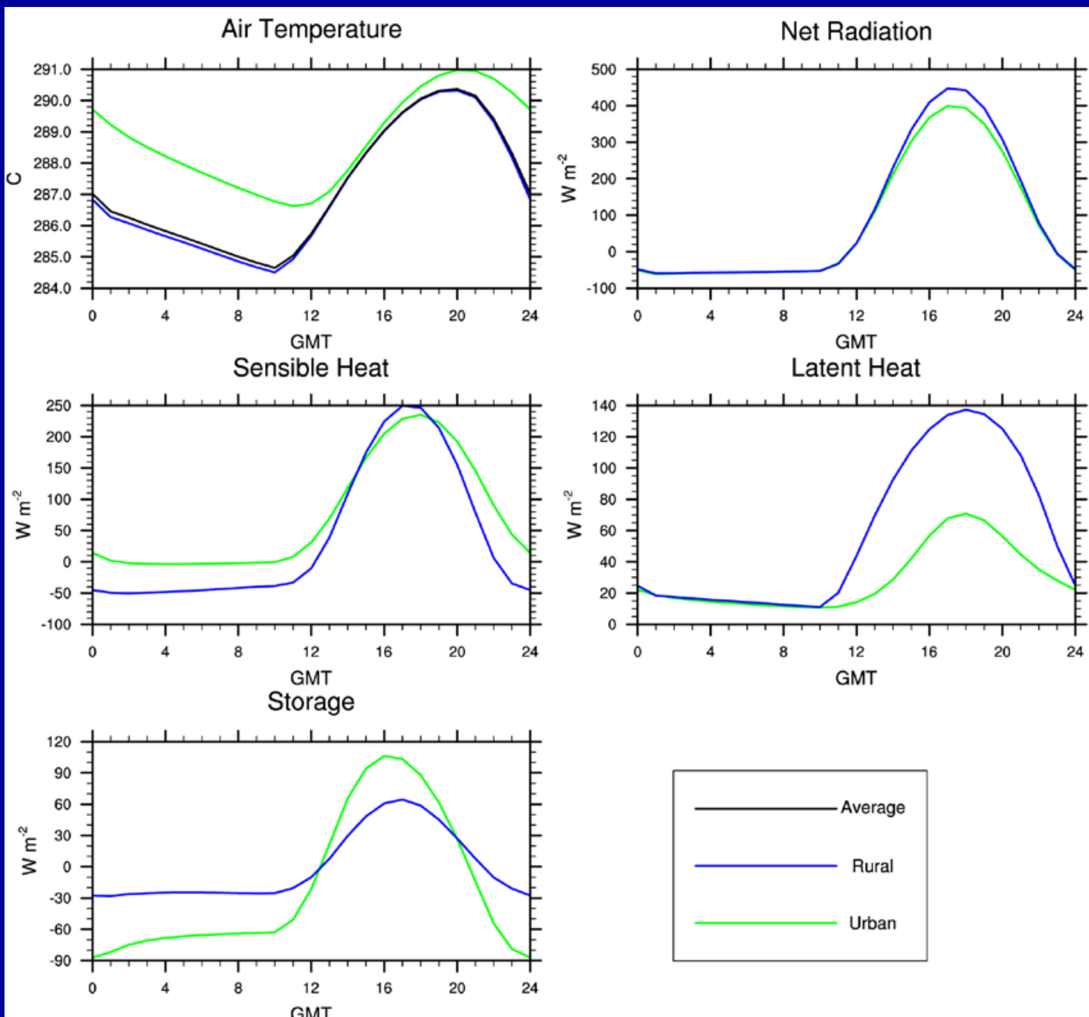
[1]AR4 A2 scenario multi-model ensemble mean

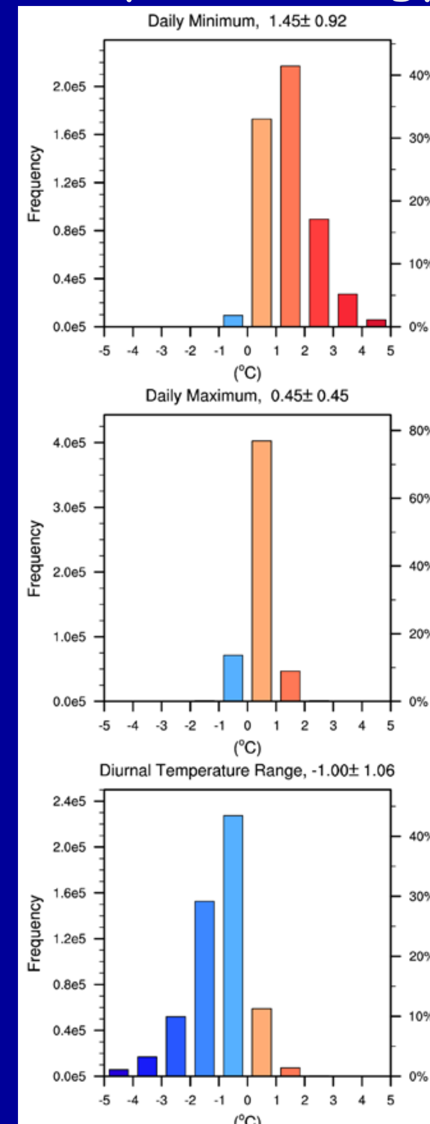
Energy Balance and Diurnal Temperature

NWHF

Global Urban – Rural Daily Climatology

1980-1999 Annual Diurnal Cycle (40.7N, 287.5E)

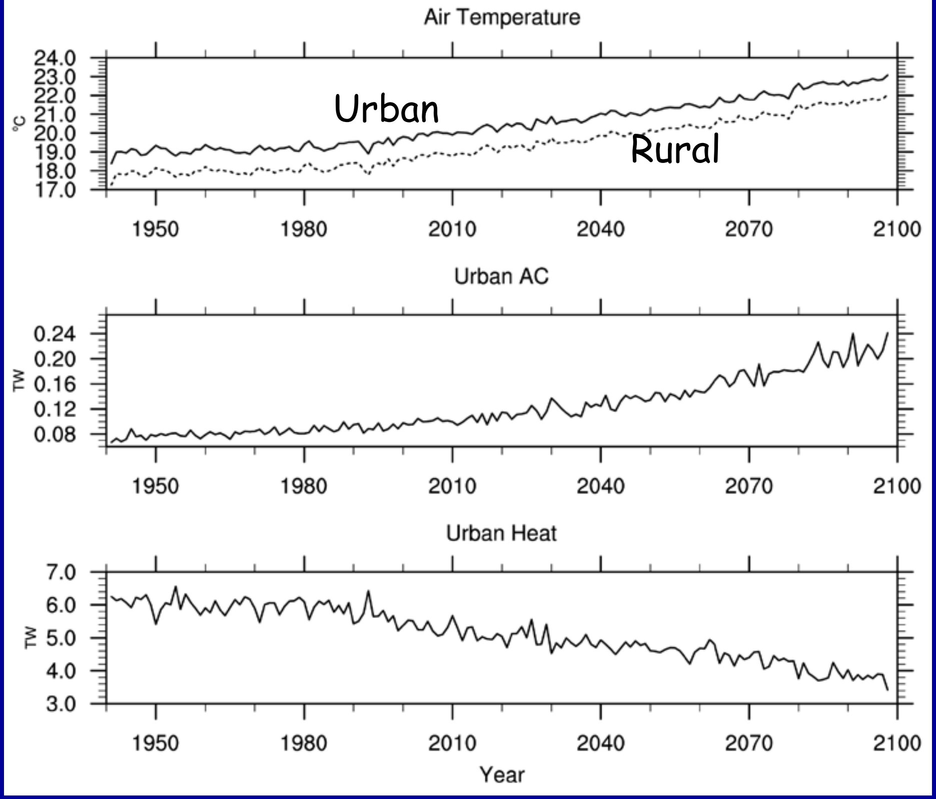


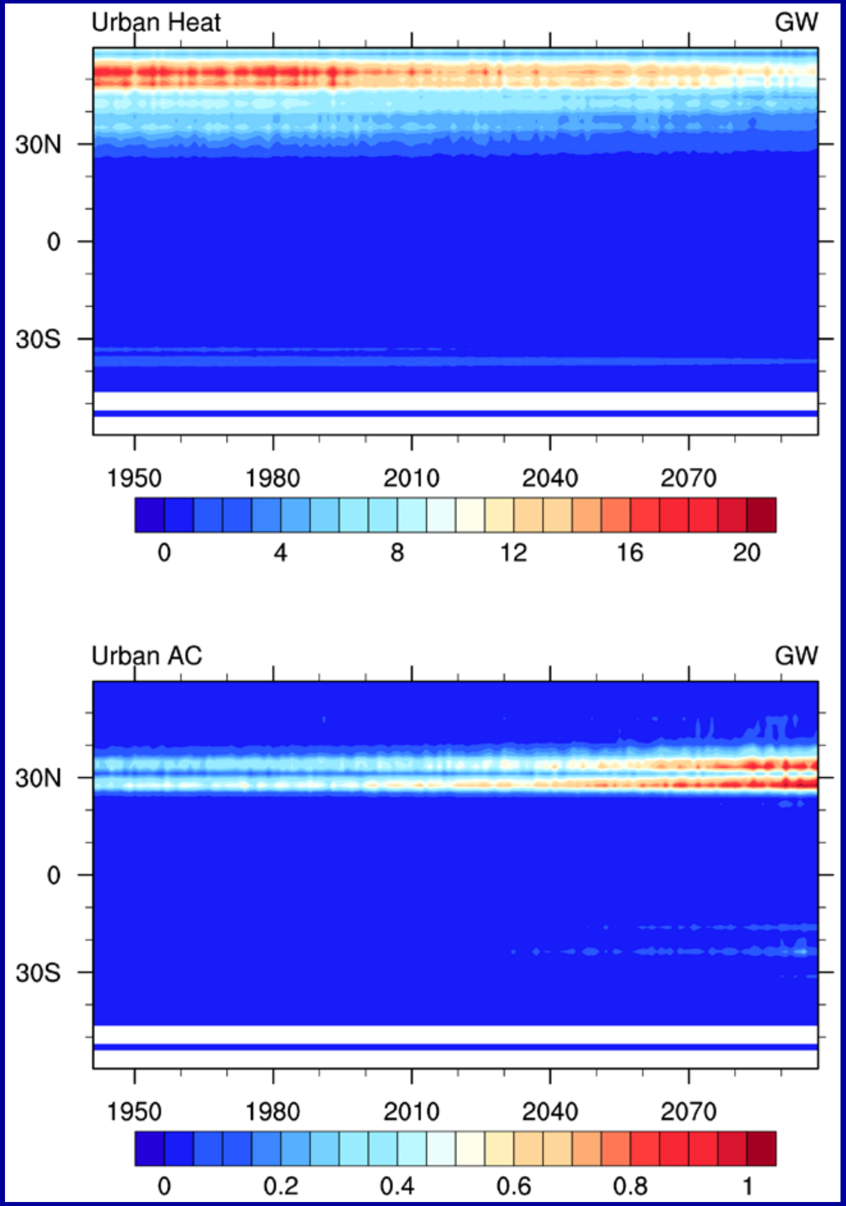


Heating and AC Fluxes

NWHF

Global Annual Trends

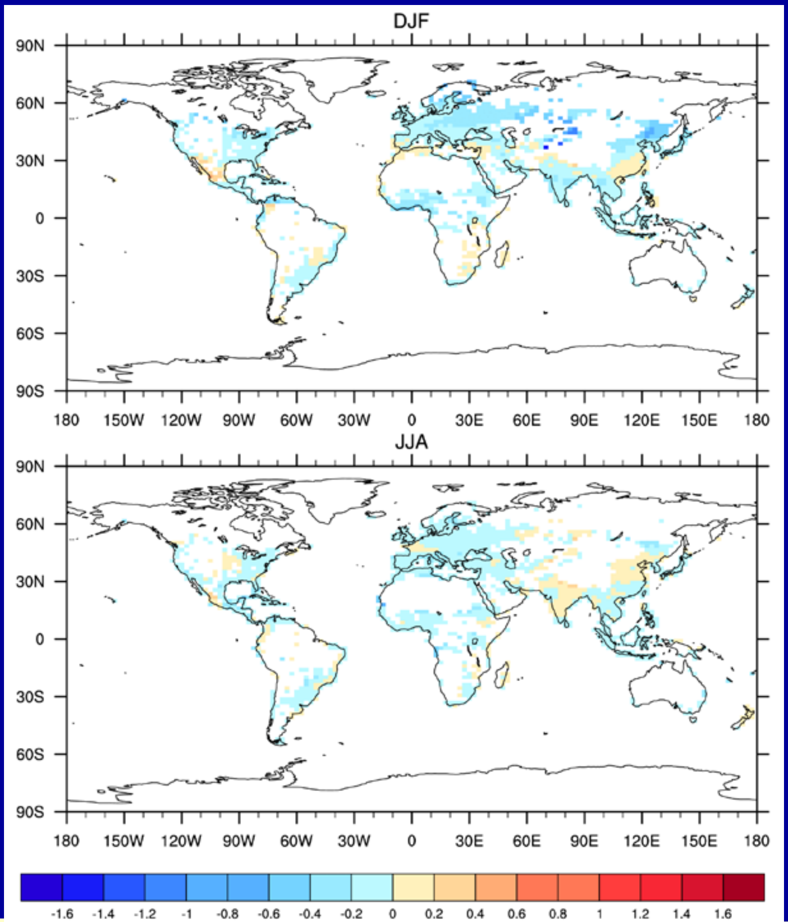




Average Urban Heat Island Decreasing in Warming Climate

NWHF

2079-2098 — 1980-1999
Urban Heat Island

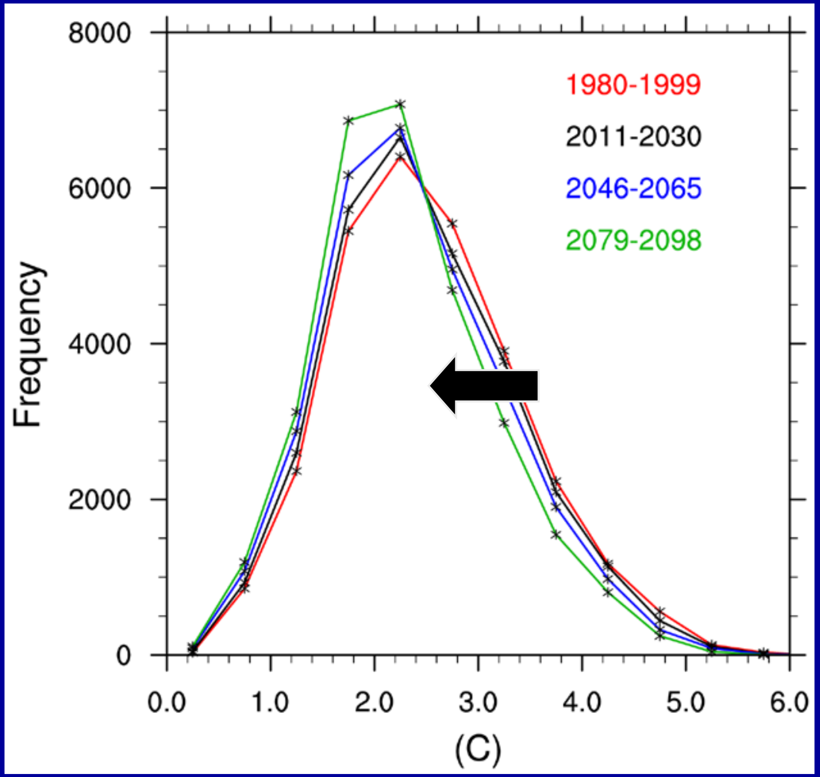


-1.6 1.6

82% significant at 0.01 level

76% significant at 0.01 level

Annual Average of Daily
Maximum Urban Heat Island

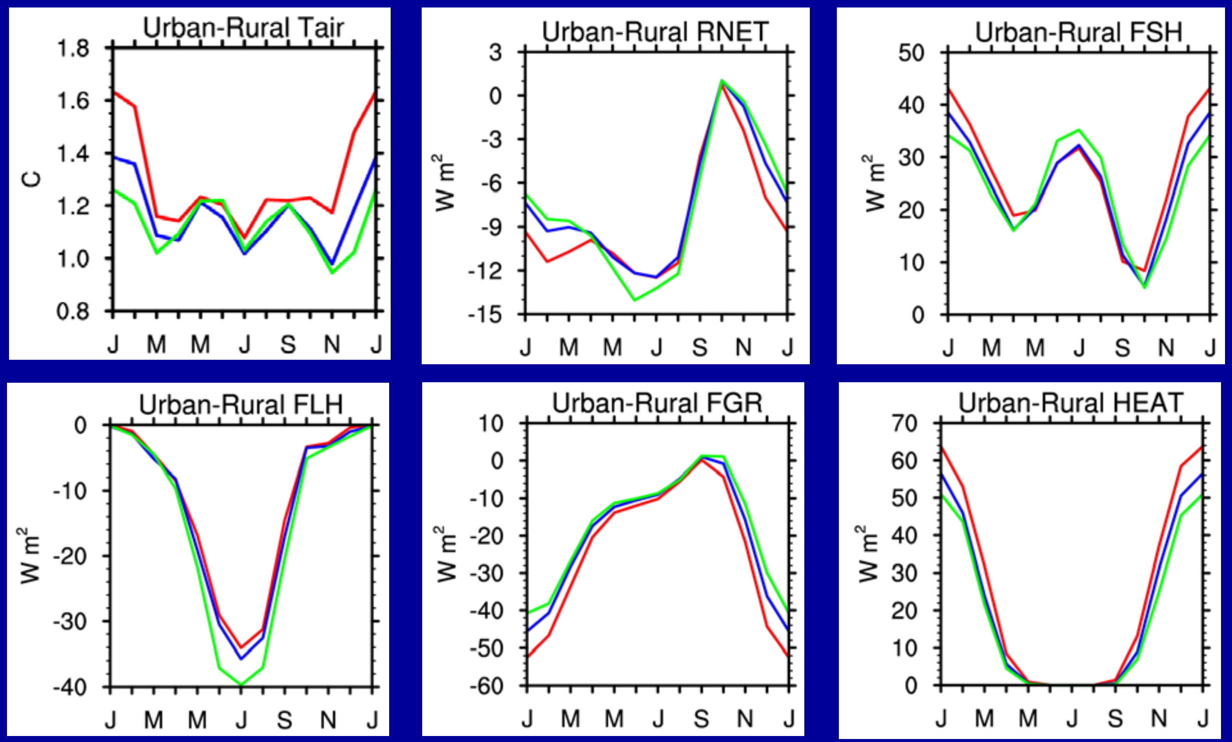


20 yrs X 1434 gcl

Effects of Changes in Building Heat

NWHF

Northeast China (35-50N, 118-140W)



1980-1999

2046-2065

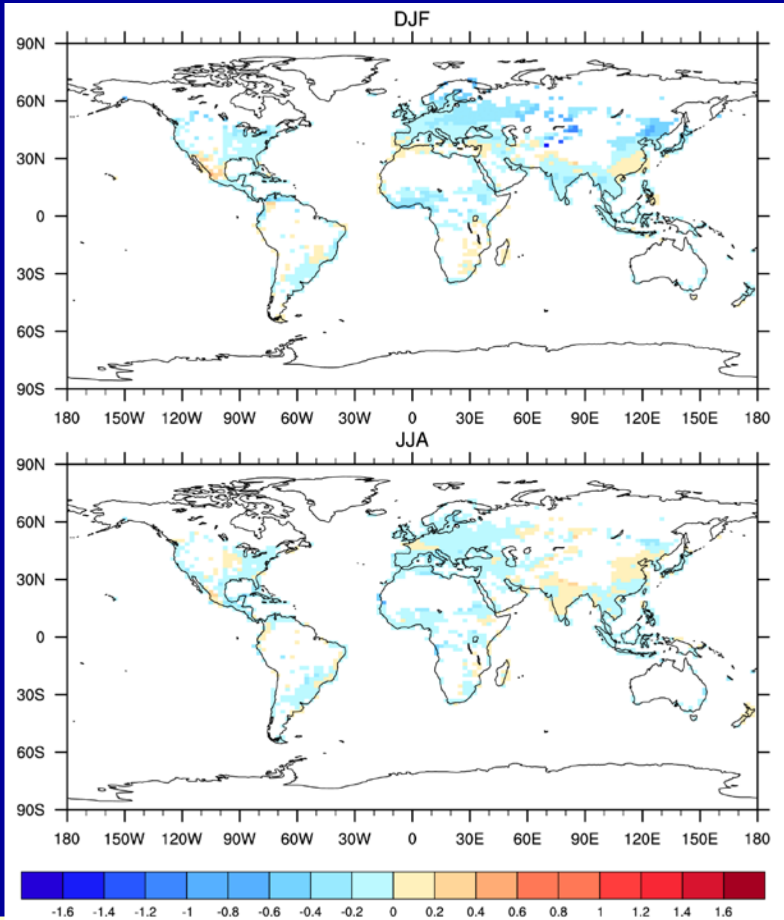
2079-2098

➢In winter, present day heat island is partially maintained by building heat. In warming climate less heating is required to keep buildings warm which reduces urban-rural contrast

Effects of Changes in Incident Solar Radiation

NWHF

2079-2098 — 1980-1999
Urban Heat Island (C)



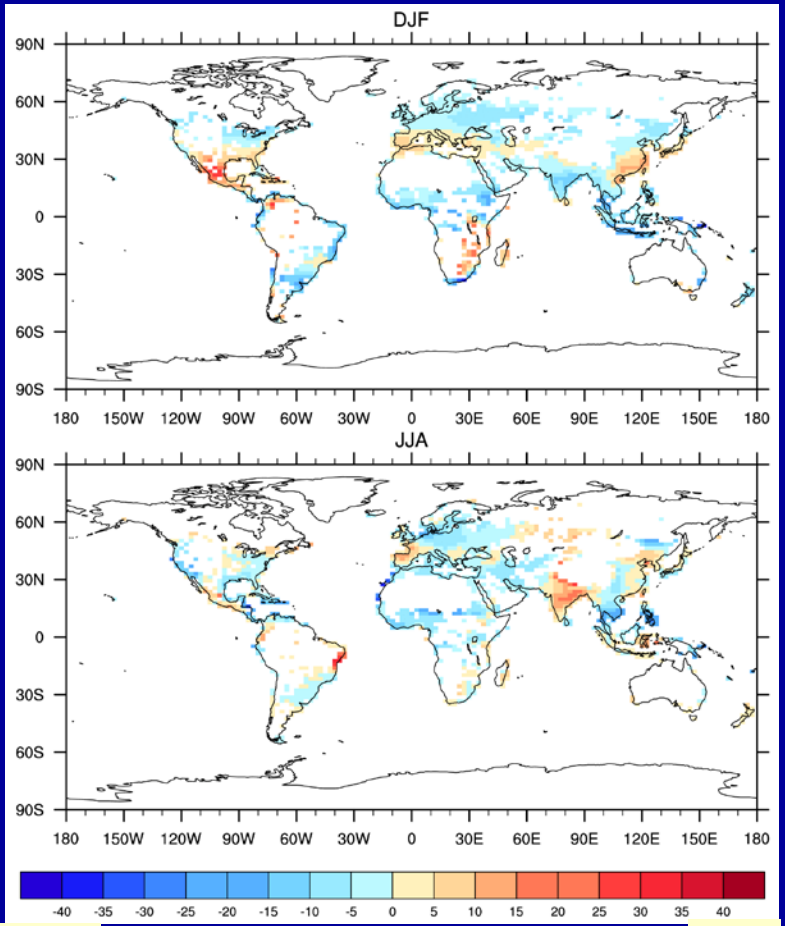
R=0.39

R=0.42

-1.6

1.6

2079-2098 — 1980-1999
Incident Solar Radiation (W m^{-2})



-40

40

Cooling the World with White Roofs

“There’s a friend of mine, a colleague of mine, Art Rosenfeld, who’s pushing very hard for a geo-engineering we all believe will be completely benign, and that’s when you have a flat-top roof building, make it white.

“Now, you smile, but he’s done a calculation, and if you take all the buildings and make their roofs white and if you make the pavement more of a concrete type of colour rather than a black type of colour, and you do this uniformly . . . it’s the equivalent of reducing the carbon emissions due to all the cars on the road for 11 years.”

Steven Chu, U.S. Energy Secretary (as quoted in TimesOnline, May 27, 2009)

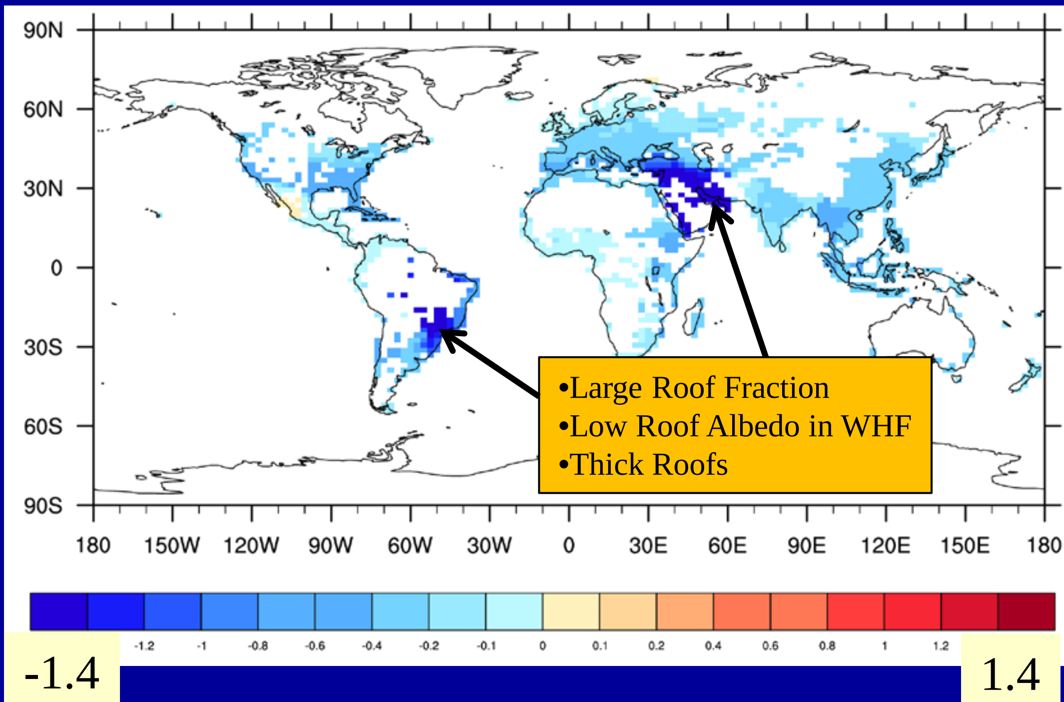
Onetime offset of 44 Gt of CO2 emissions from increasing roof albedo by 0.25 and pavement albedo by 0.15, equivalent to taking all cars off the road for 18 years (Akbari et al. 2009, Climatic Change).

What happens in the model if we increase roof albedo (choose max reflective surface with albedo of 0.9)?

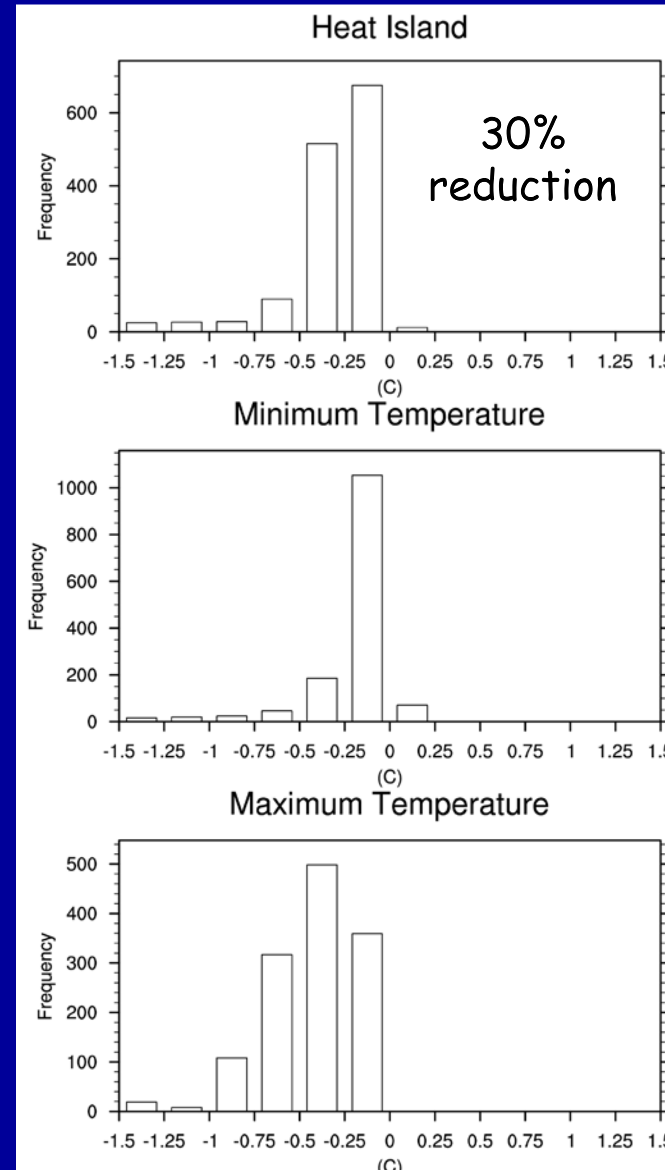
Cooling the World with White Roofs

1980-1999

WHF_ALB – WHF Annual Urban Heat Island (C)



WHF_ALB – WHF Annual



	Energy Consumption (TW)		
	HEAT	AC	TOTAL
WHF_ALB	6.30	0.02	6.32
WHF	5.61	0.09	5.70

Conclusions

- Average UHIs of near-zero up to 4°C are produced by model with seasonal and spatial variations. Average present-day UHI is comparable to 2011-2030 global warming projections.
- Diurnal temperature range in urban areas smaller compared to rural areas due to warmer minimum than maximum temperature.
- Without consideration of other anthropogenic heat sources or future urban growth scenarios, average UHI decreases in warming climate. At high latitudes, decline in urban heating reduces urban-rural contrast.

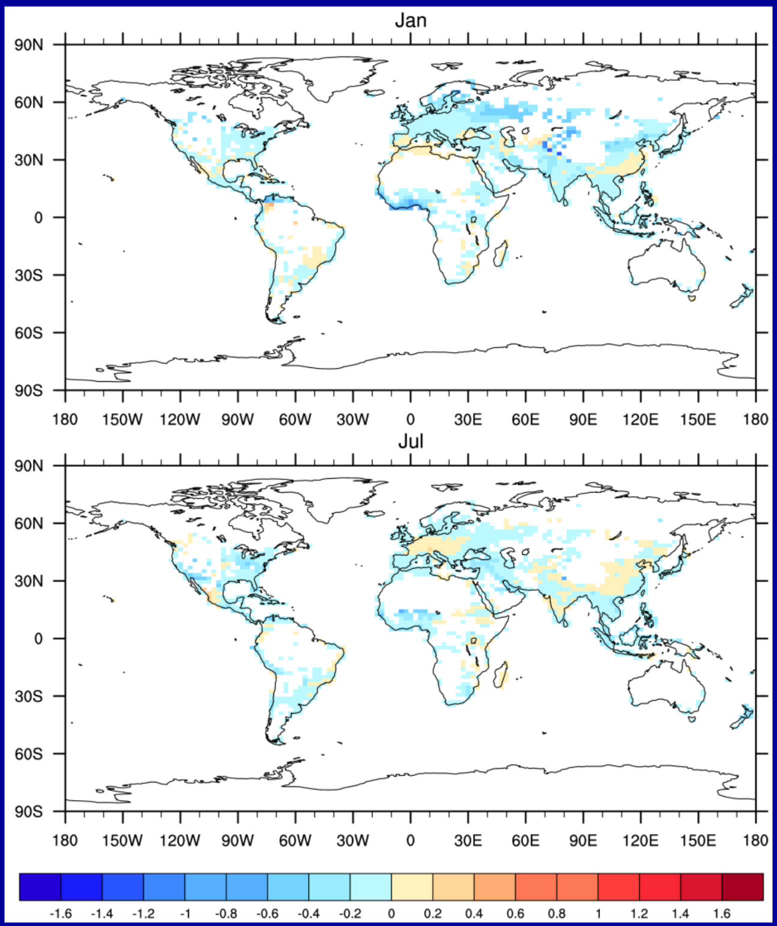
  This implies that future heat islands can't be predicted by imposing present day heat islands on climate change simulations (Betts and Best 2004)
- Total energy consumption for HAC declines in a warming climate
- Inclusion of wasteheat fluxes generally results in a larger UHI (about 5% in global mean UHI).
- Increasing global roof albedo to 0.9 reduces present-day annual mean UHI by 30% but increases energy consumption by about 10%

Extra Slides

Urban Heat Island Decreasing in Warming Climate

NWHF

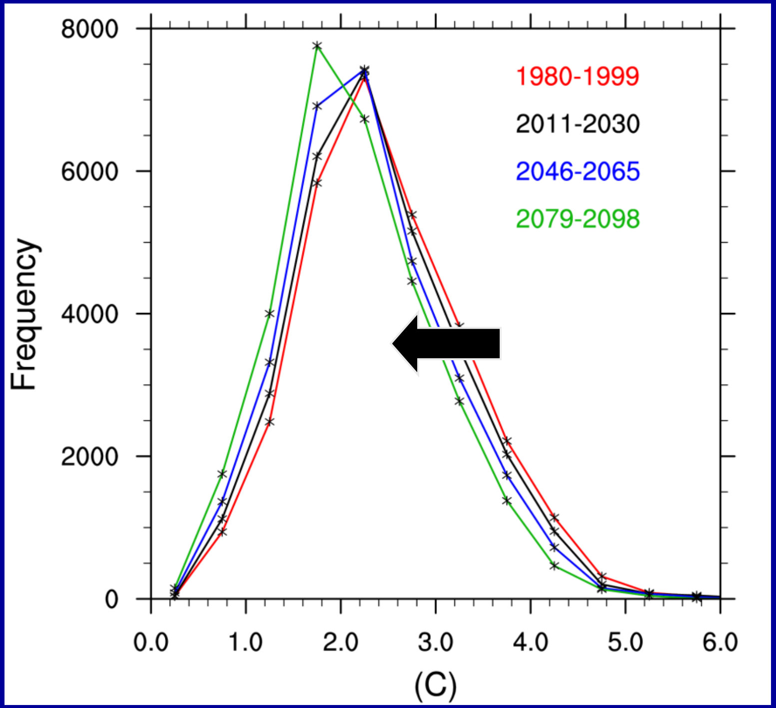
2046-2065 — 1980-1999
Urban Heat Island



-1.6

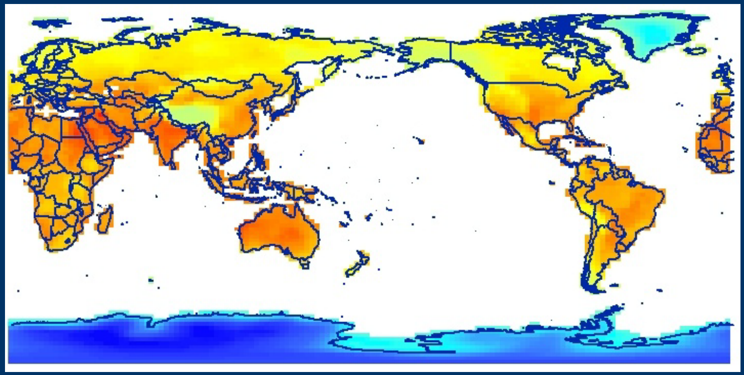
1.6

Annual Average of Daily
Maximum Urban Heat Island

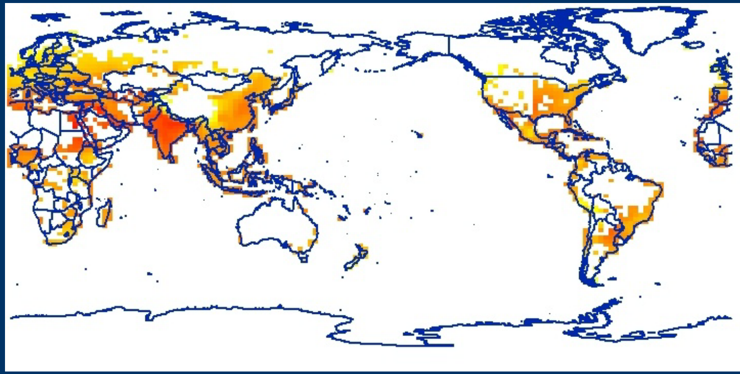


Heat events

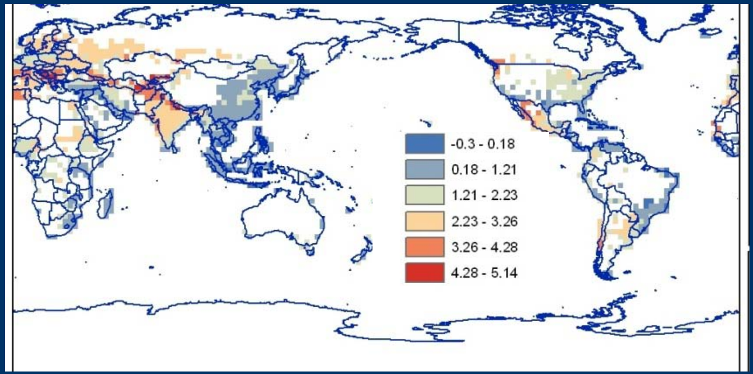
- **Heat events: Severity of an annual "worst heat event" (Meehl and Tebaldi, 2004 *Science*).**
  - several consecutive nights with no relief from very warm nighttime minimum temperatures important for health impacts.
- **The means of three consecutive warmest nights for urban and rural runs**
  - present-day climate (1980-1999)
  - 2030 (2020-2039)



"Rural" simulation (w/o heat island)



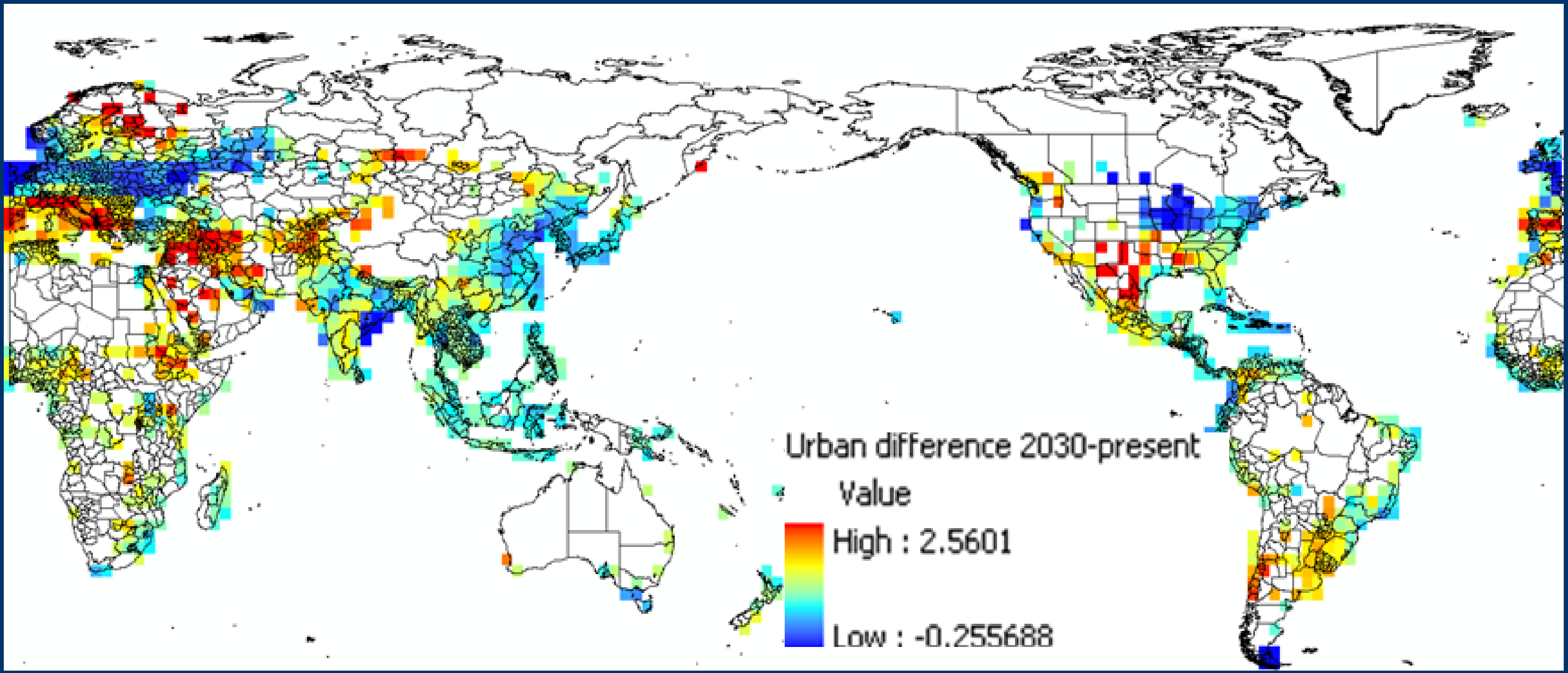
"Urban" simulation



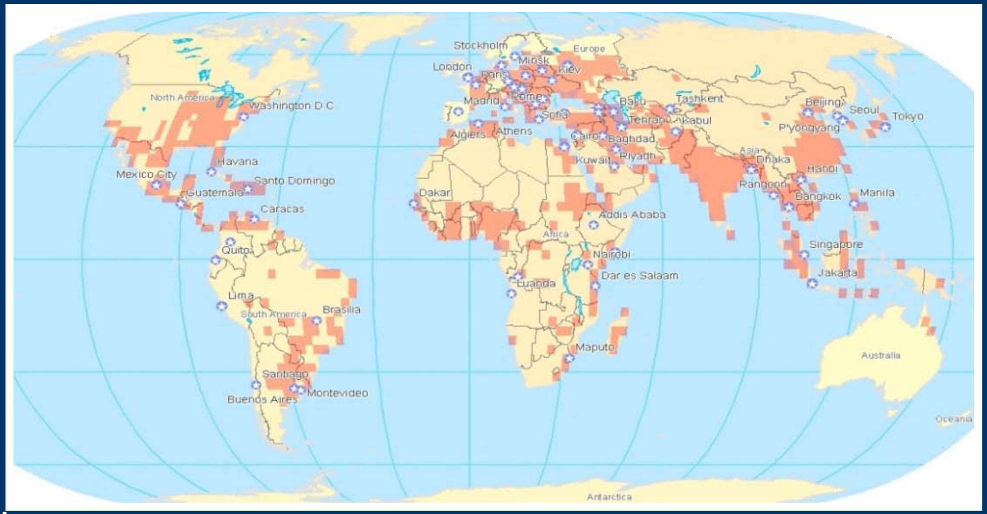
"Urban"-"Rural" difference of worst heat event

Projected changes in annual worst heat events

- **Increased severity of the worst annual heat events in most urban areas by 2030 according to model simulations of AR4 A2 scenario**



Projected changes in annual worst heat events



Present-day

2030

> 20C

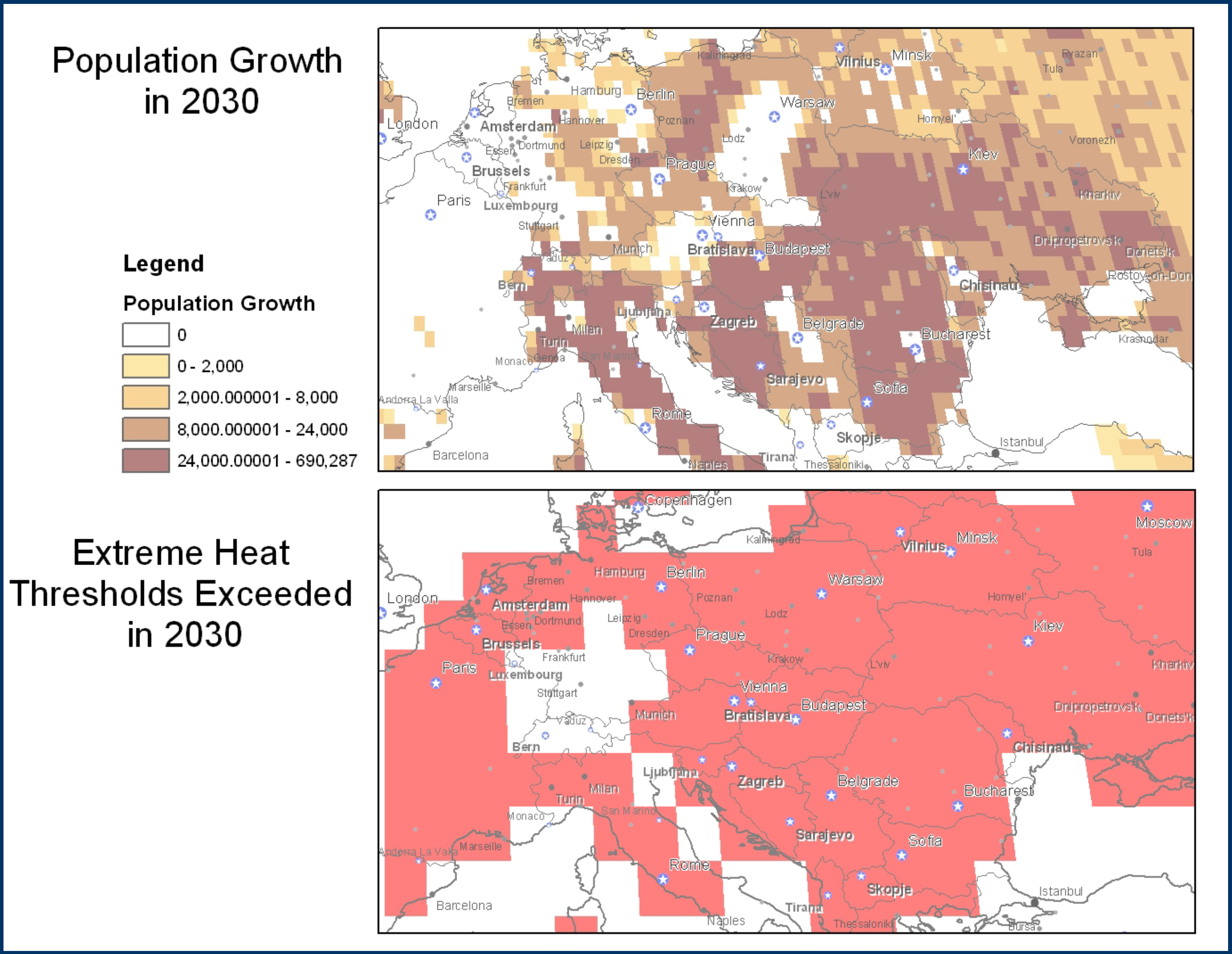
Present-day

2030

> 25C

- **No major geographic shifts in increased exposure to excessive heat**
- **Increased spatial extent in most regions (minimum temperature threshold depending)**

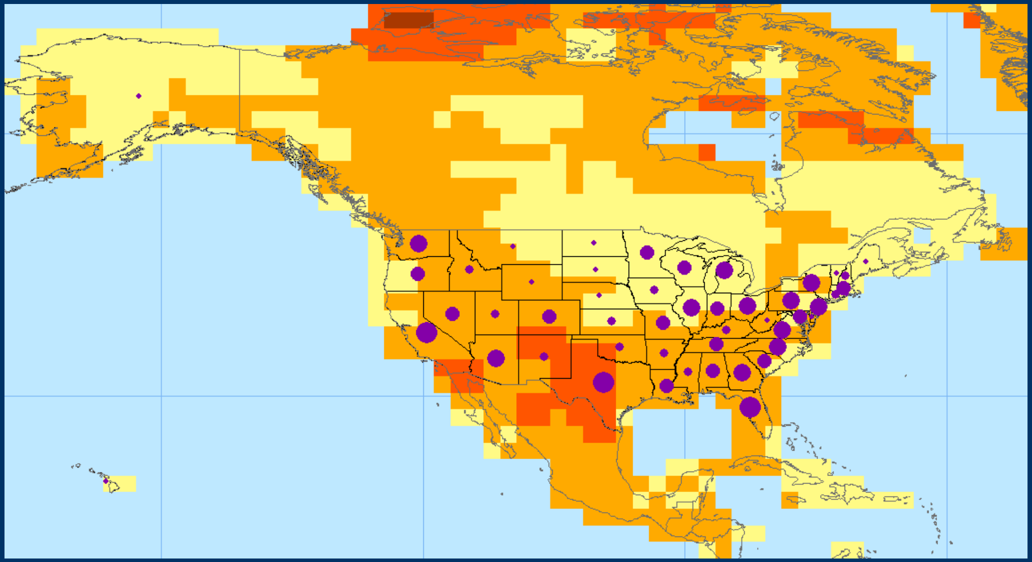
Potential Impact on Population

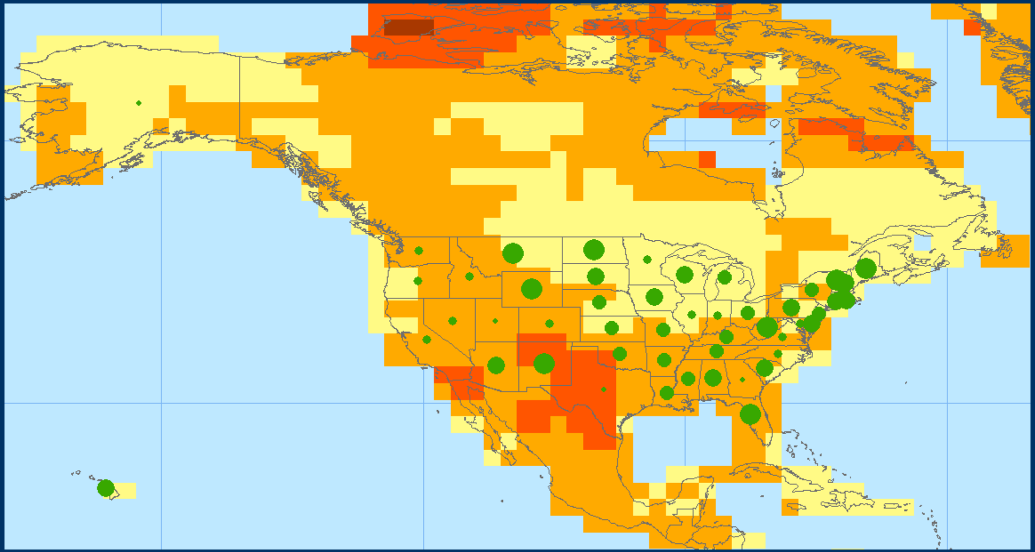


Source of gridded population projections: IIASA; Brian O'Neil (NCAR)

Due to population growth and increase in spatial extent of worst heat events in 2030 additional 50M people maybe exposed to excessive heat events

Potential Impact on Vulnerable Populations





Present-day – 2030 worst heat event anomaly (gridcell average)

(degrees)
- 0 - 1
- 1 - 2
- 2 - 3
- > 3

Number of people 65 and older in 2030

Percentage of people 65 and older in 2030

Future work

- Relationships between heat island and urban characteristics and meteorology to explain spatial and temporal variability
- Incorporate future urban datasets (J. Feddema)
- Explore uncertainty in urban datasets
- Effects of other anthropogenic heat sources
- Further evaluation of the model with observations (e.g., process level studies, flux tower sites, model intercomparisons)
- Mitigation of urban warming (e.g., cool materials)
- Urban extreme events in a warming world (Olga Wilhelmi and colleagues)

What is the purpose of representing urban areas in a global climate model?

- Assumption of stationarity under radiatively-forced climate change may not be valid for urban heat islands (accounting for anthropogenic heat flux).

  Heat island characteristics may change as cities evolve. Thus, changes in temperature in urban areas may be more reliably estimated by the explicit modeling of urban heat islands within climate models (Betts and Best 2004, BETWIXT Notes 3&6).

Urbanizing a global climate model

- Motivation
  - Urbanization is a significant component of anthropogenic land cover change
  - Urban areas affect local climate
  - The majority of people live in urban areas and experience urban climates
  - Urban areas are detectable at the GCM grid scale
  - Urban areas are expected to expand significantly in the near future
  - Urban areas are the main source of anthropogenic emissions
- Purpose
  - Provide climate and climate-change information (e.g., surface air temperature and humidity, surface hydrology, etc.) for urban environments, where the majority of people work and live.
  - Capture observed features of urban climate and provide insight into the physical mechanisms underlying these features

Urban Heat Island Processes

Represented

- Increased shortwave absorption due to trapping inside canyon (lower albedo)
- Decreased loss of heat by turbulence due to stagnation in deep canyon
- Decreased surface longwave radiation loss due to reduction of sky view factor
- HAC and wasteheat
- Reduction of ET due to replacement of vegetation with impervious surfaces
- Increased storage of sensible heat due to larger thermal admittance of urban materials
- Reduced transfer of heat due to sheltering from buildings

Not Represented

- Effects of pollution on downward longwave and solar radiation
- Urban boundary layer heat island
- Other sources of anthropgenic heat

Model Evaluation

- Global observations to evaluate the model are simply unavailable. Therefore, strategy is to develop confidence in the model through bottom-up studies:
- Process-level studies – e.g., 1) evaluation of canyon albedo, 2) many of CLMU parameterizations are taken from CLM when urban and vegetation/soil/snow treatments are expected to be similar because CLM is a well-tested model.
- Reasonable performance when evaluated against measured energy balance fluxes and temperatures for two urban sites (Oleson et al. 2008a)
- Preliminary results from International Urban Surface Energy Balance Model Comparison Study indicate?
- CLMU captures typical observed characteristics of urban climates (e.g., heat islands) qualitatively (Oleson et al. 2008b)
- Heat island evaluation using well-described urban/rural station pairs from GHCN?

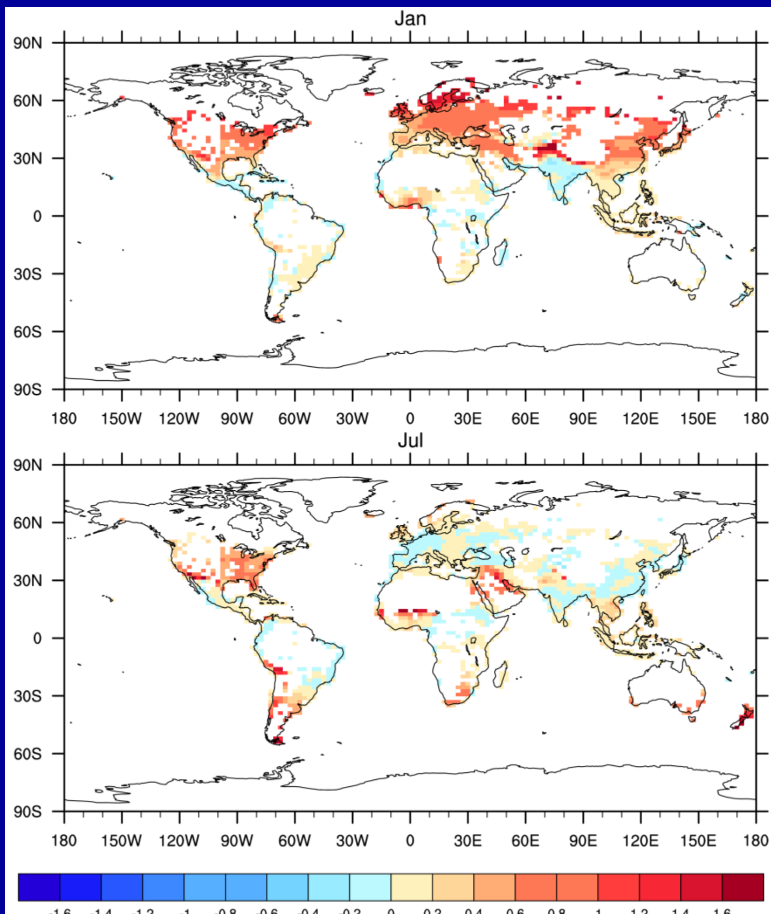
Science Questions

1. What are the effects of including urban landcover in a climate model on present day climate?
2. What are the characteristics of the urban heat island under various conditions?
3. What are the effects of current and projected urban landcover compared to present day urbanization?
4. What are the effects of current and projected anthropogenic heat sources on climate?
5. How sensitive is the urban climate to different representations of urban structure and future growth?
6. What are the effects of mitigation and adaptation strategies?
7. How do present day urban heat islands compare to global warming scenarios?
8. What are the effects of anthropogenic heat sources on urban climate?

Effects of Wasteheat Fluxes on Urban Heat Island

1980-1999

WHF – NWHF Urban Heat Island (C)



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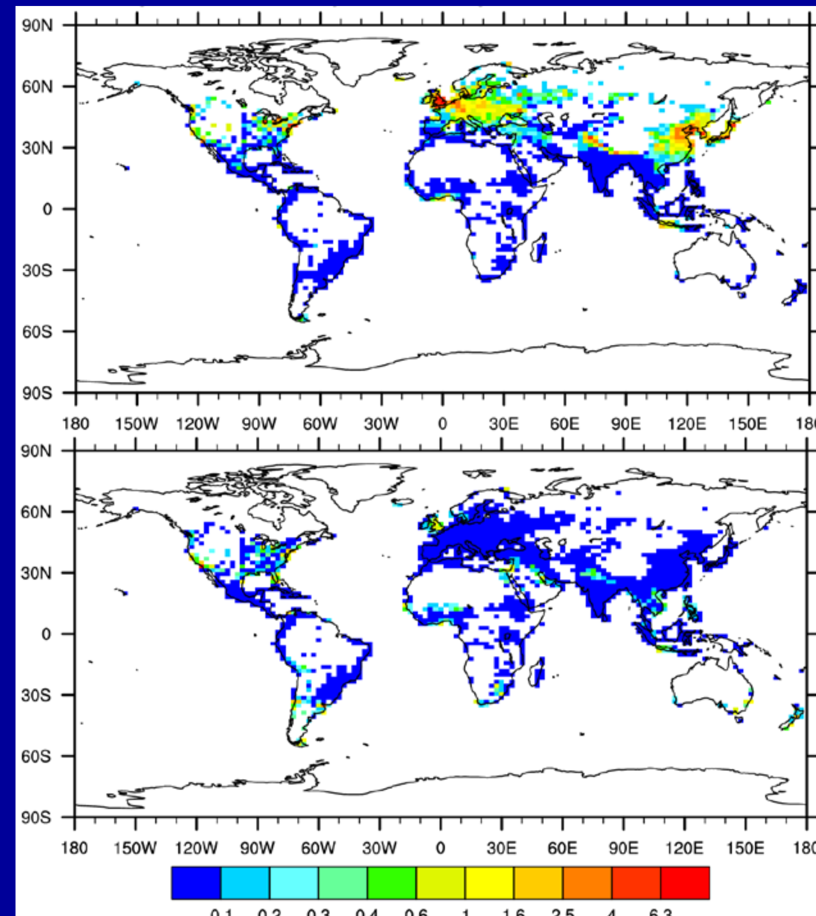
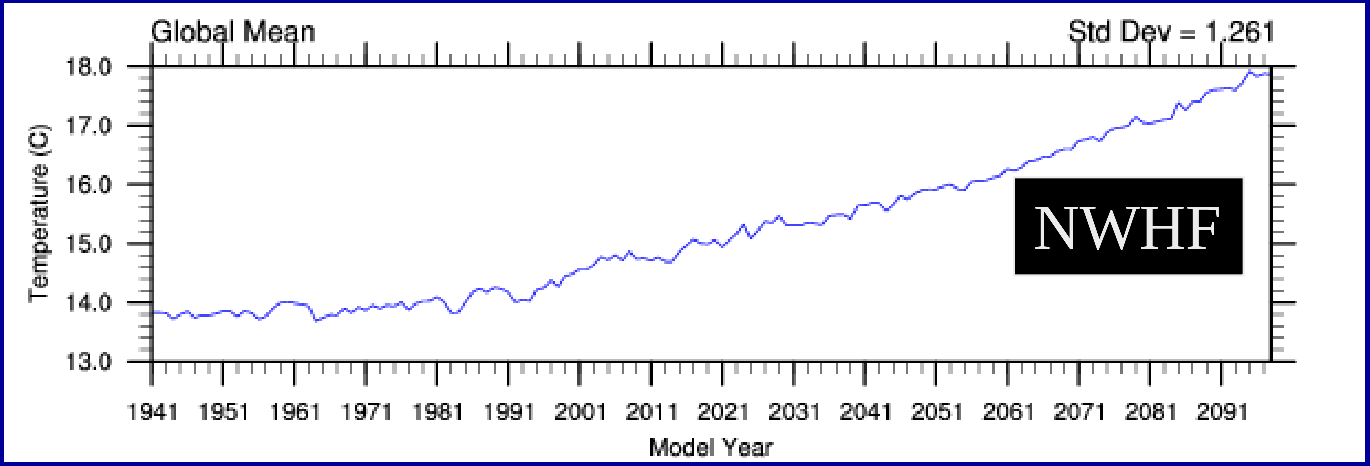
1.6

Wasteheat Flux (W/m2)



Global Surface Air Temperature



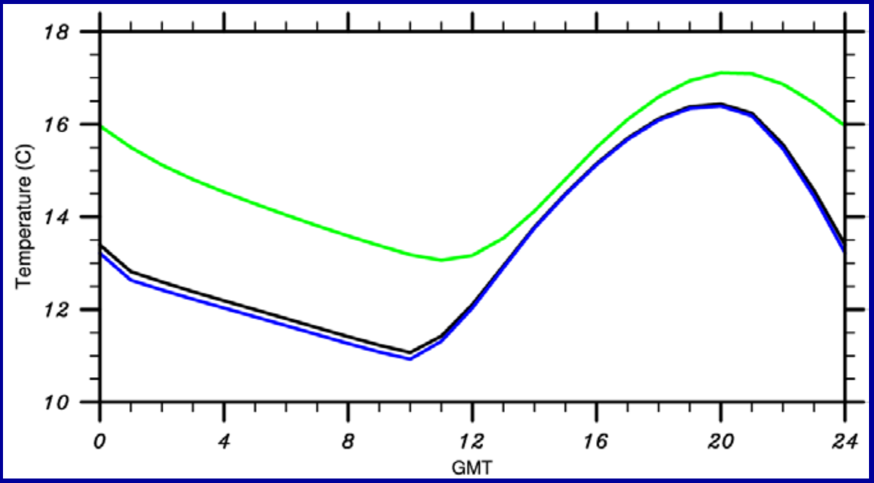
Difference (°C) from Base Period (1980-1999)

	2011-2030	2046-2065	2079-2098
NWHF	0.94 (1.15)	1.96 (2.44)	3.41 (4.20)
AR4 A2 scenario multi-model ensemble mean	0.64	1.65	3.13

Aspects of Diurnal Temperature

NWHF

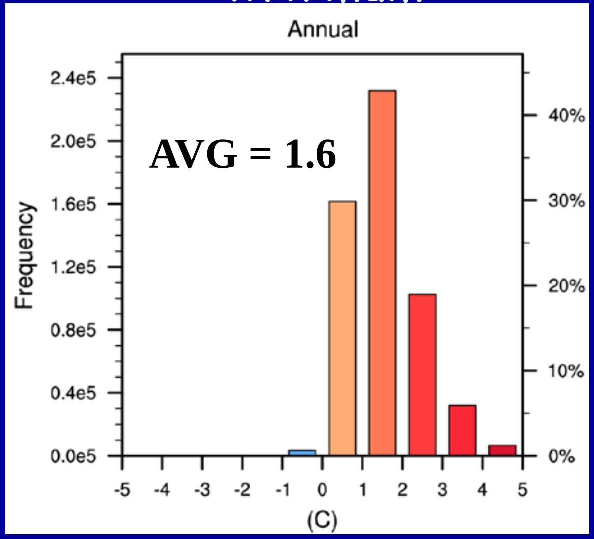
1980-1999 Average Annual Diurnal Cycle (40.7N, 287.5E)



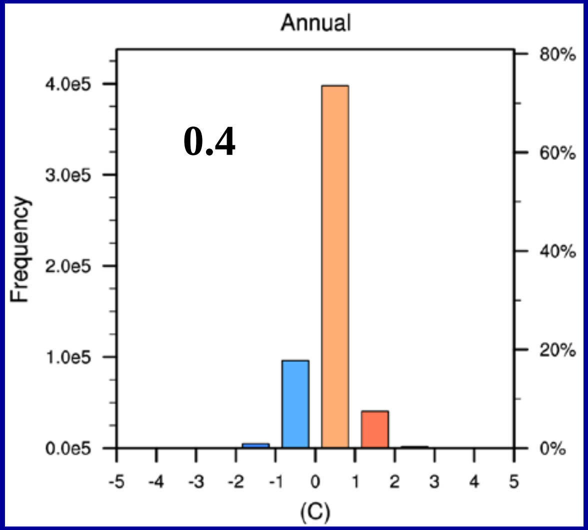
Urban
Grid Average
Rural

Urban — Rural Daily 1980-1999 Climatology

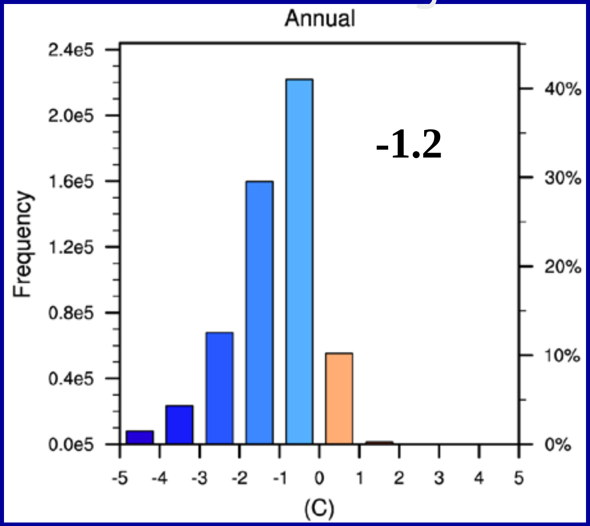
Minimum



Maximum



Diurnal Range



Urban Heat Island Compared to Projected Warming

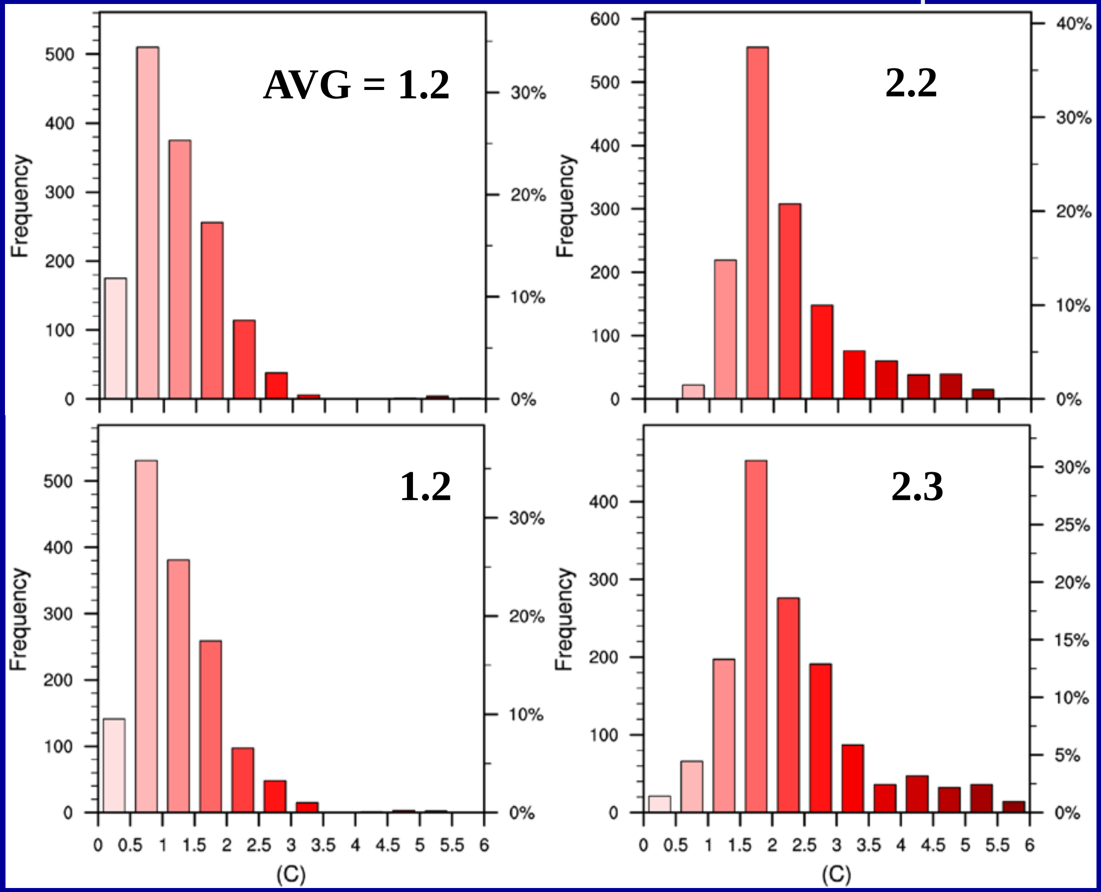
NWHF

1980-1999 Urban Heat Island

2046-2065 — 1980-1999 Surface Air Temperature

JAN

JUL

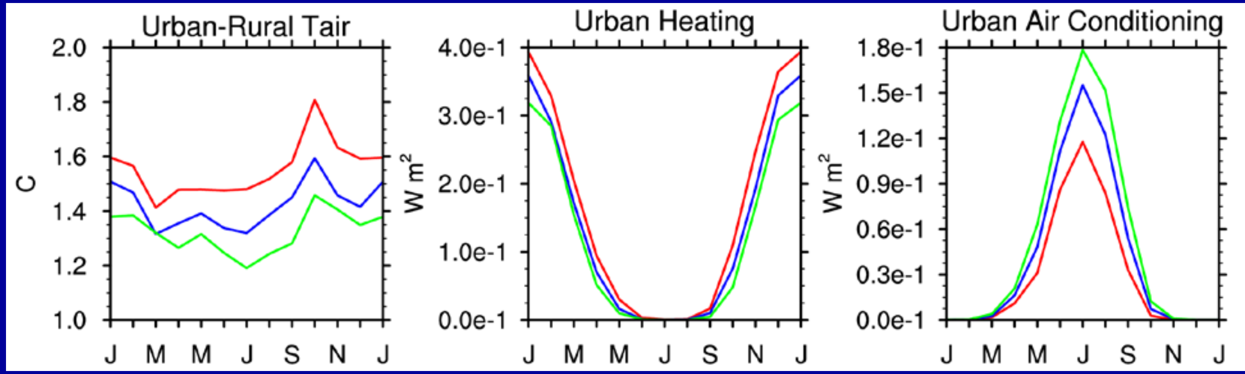


➢Magnitude of present day (1980-1999) urban heat island is significant percentage of projected future (e.g., 2046-2065) warming.

Effects of Wasteheat Fluxes on Urban Heat Island

Eastern U.S. (30-50N, 90-70W)

NWHF

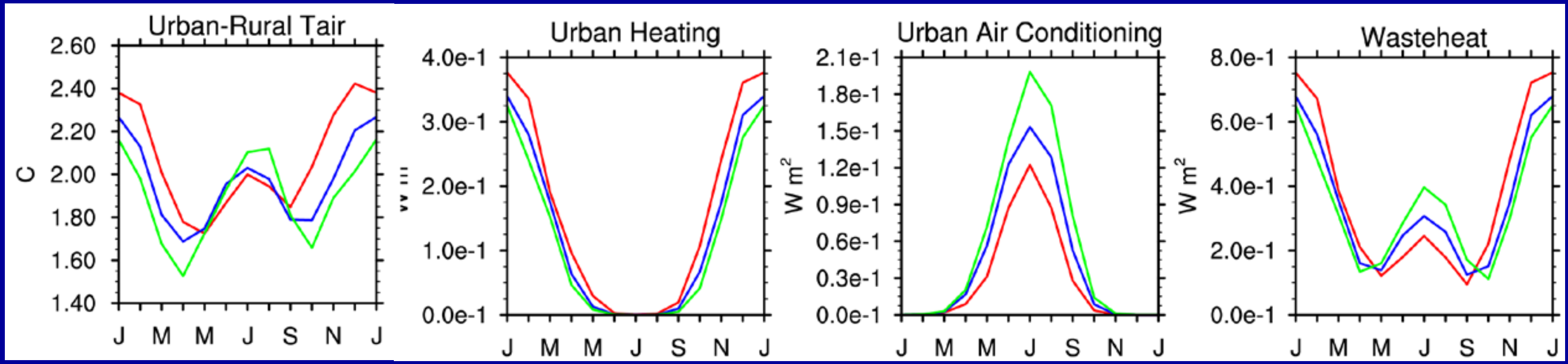


1980-1999

2046-2065

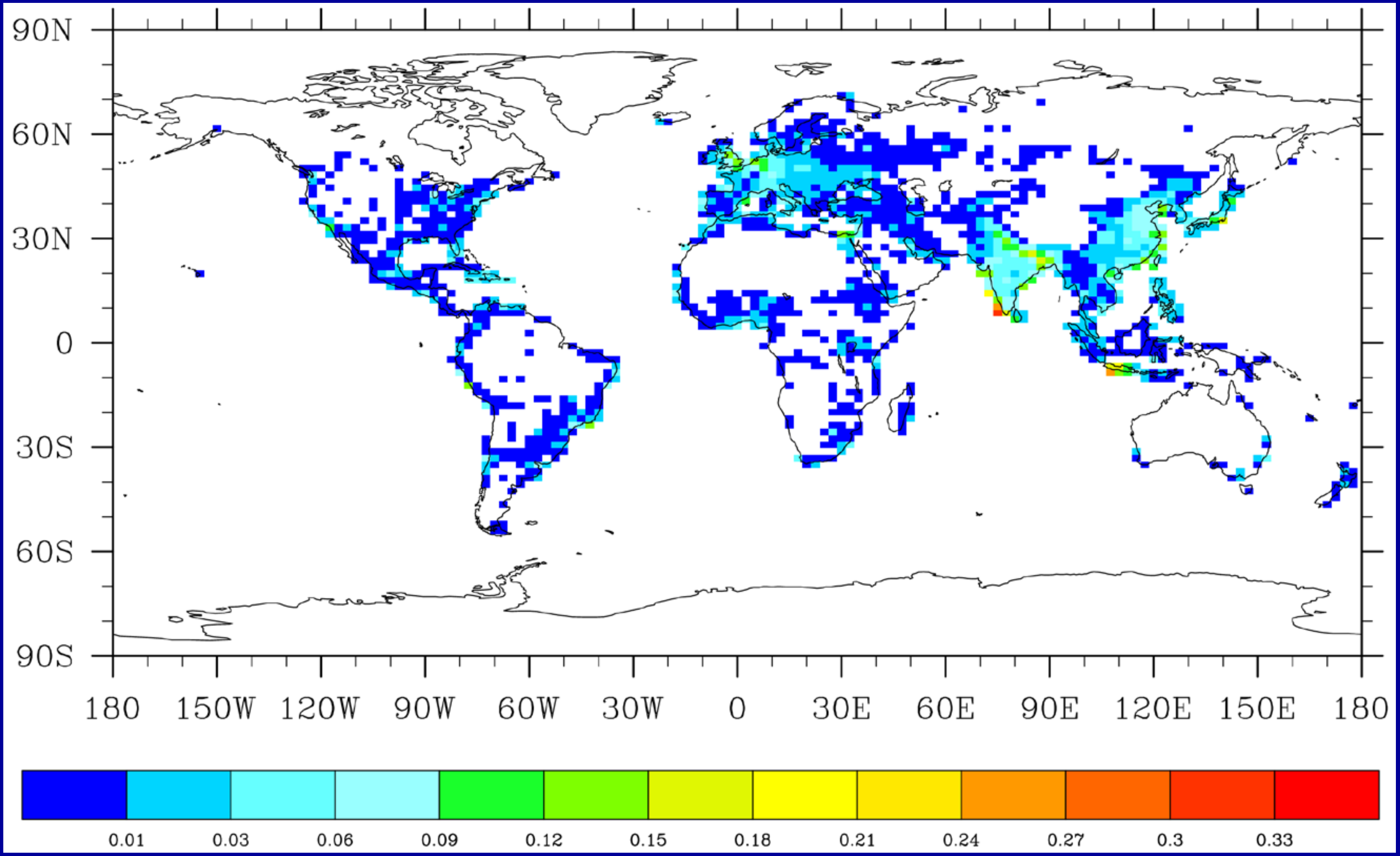
2079-2098

WHF

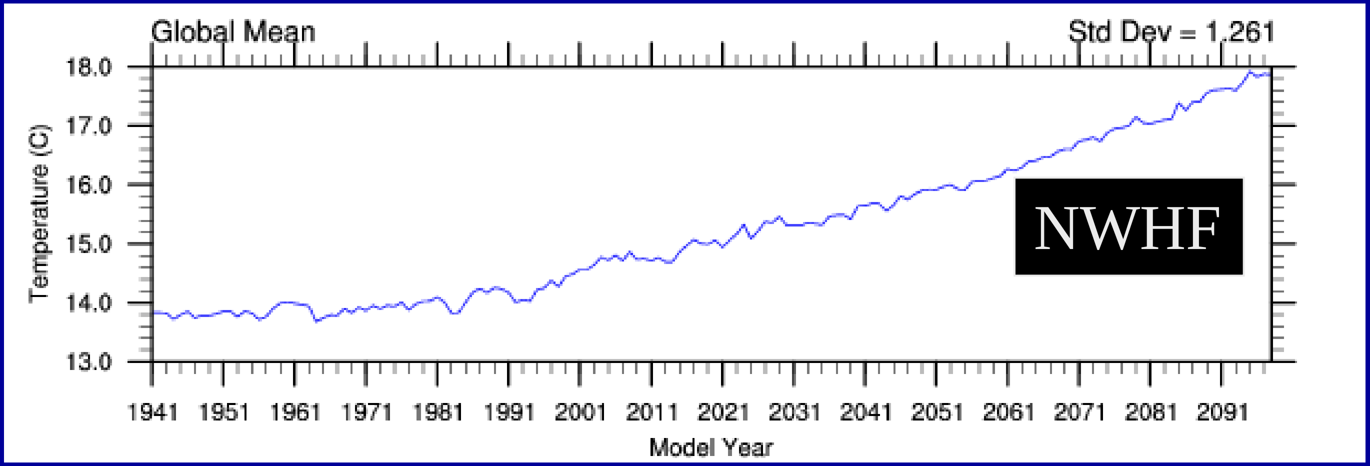


- In winter, heat island decreases in warming climate
- In summer, heat island is similar to slightly higher in warming climate

Urban Fraction at 1.9°X2.5°



Global Surface Air Temperature



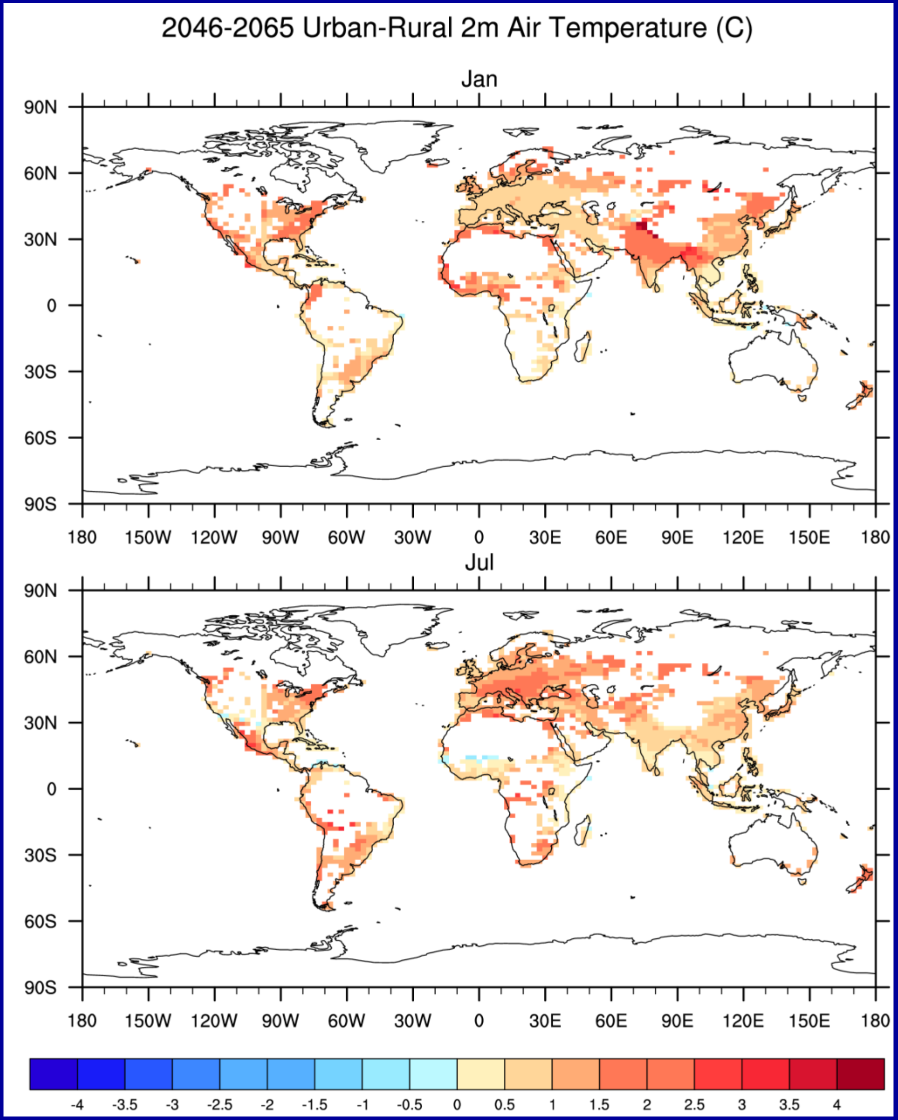
Difference (°C) from Base Period (1980-1999)

	2011-2030	2046-2065	2079-2098
NWHF	0.94 (1.15)	1.96 (2.44)	3.41 (4.20)
WHF	0.94 (1.14)	1.97 (2.45)	3.41 (4.20)
AR4 A2 scenario multi-model ensemble mean	0.64	1.65	3.13

WHF-Wasteheat Flux

Urban Heat Island Patterns

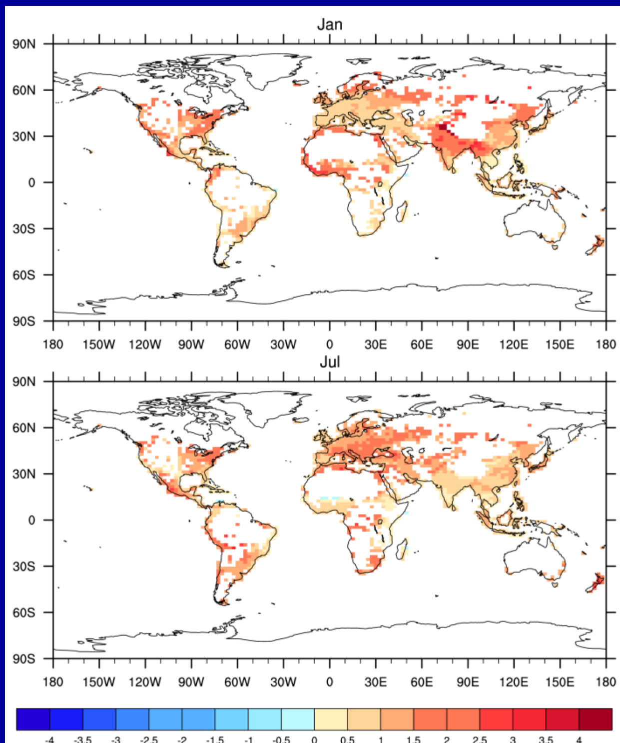
Monthly Average Climatology



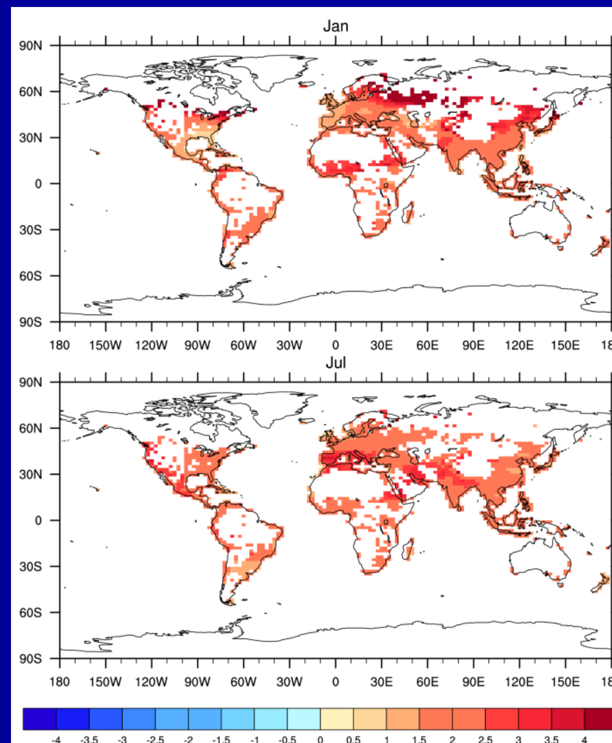
Urban Heat Island Compared to Projected Warming

NWHF

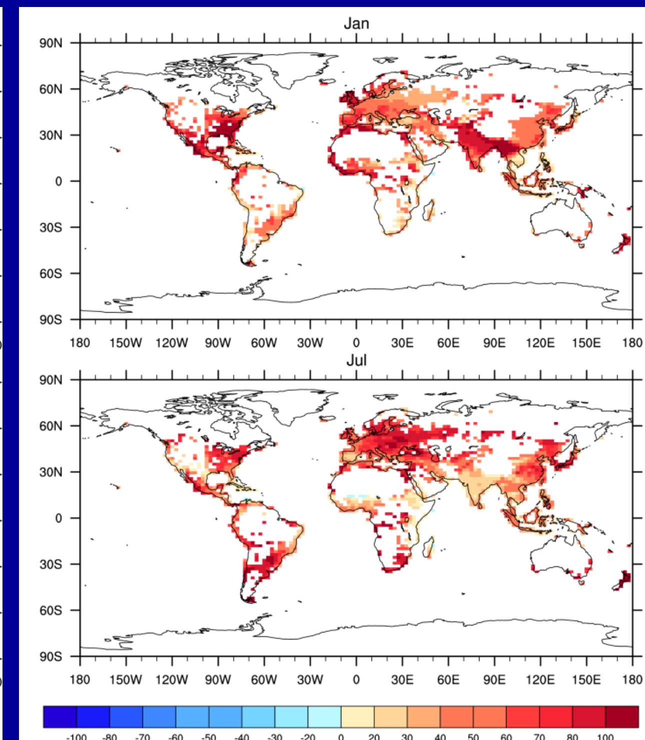
1980-1999 Urban Heat Island



2046-2065 – 1980-1999
Surface Air Temperature



1980-1999 Urban Heat Island
as % of 2046-2065 warming



- Magnitude of present day (1980-1999) urban heat island is significant percentage of projected future (e.g., 2046-2065) warming.

Urban Heat Island Decreasing in Warming Climate

NWHF

% of days with Tmin exceeding 20°C

	1980-1999	2046-2065	2079-2098
Urban	39.7	46.7	51.4
Rural	33.5	41.1	46.4
Urban-Rural	6.2	5.6	5.0

% of days with Tmax exceeding 30°C

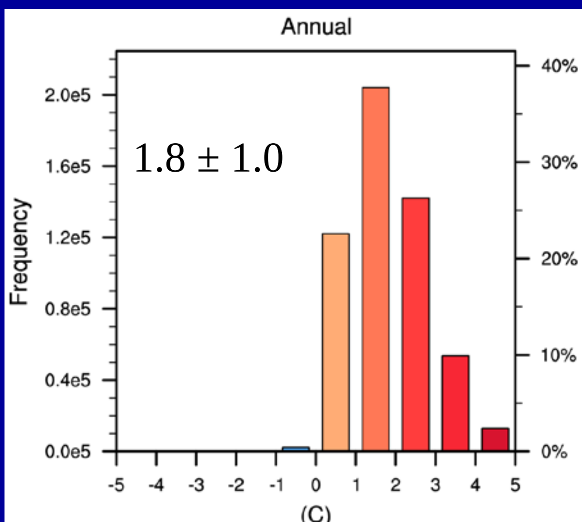
	1980-1999	2046-2065	2079-2098
Urban	17.3	28.9	37.0
Rural	15.3	27.0	35.4
Urban-Rural	2.0	1.9	1.6

Diurnal Temperature Range

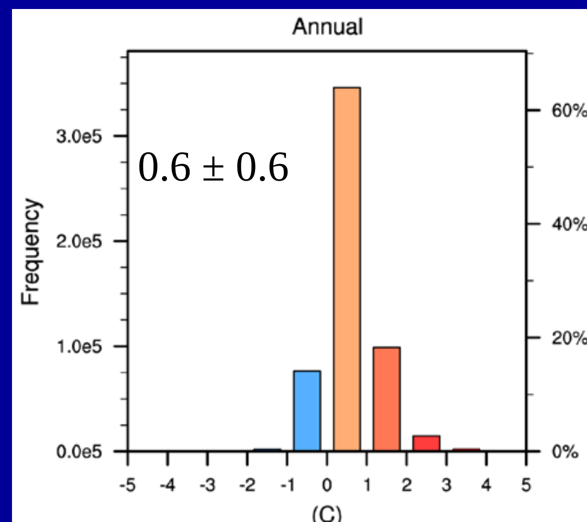
WHF

Urban-Rural 1980-1999 Daily Climatology

Minimum



Maximum



Diurnal Range