Representing urban areas and heat stress in global climate models (CESM)

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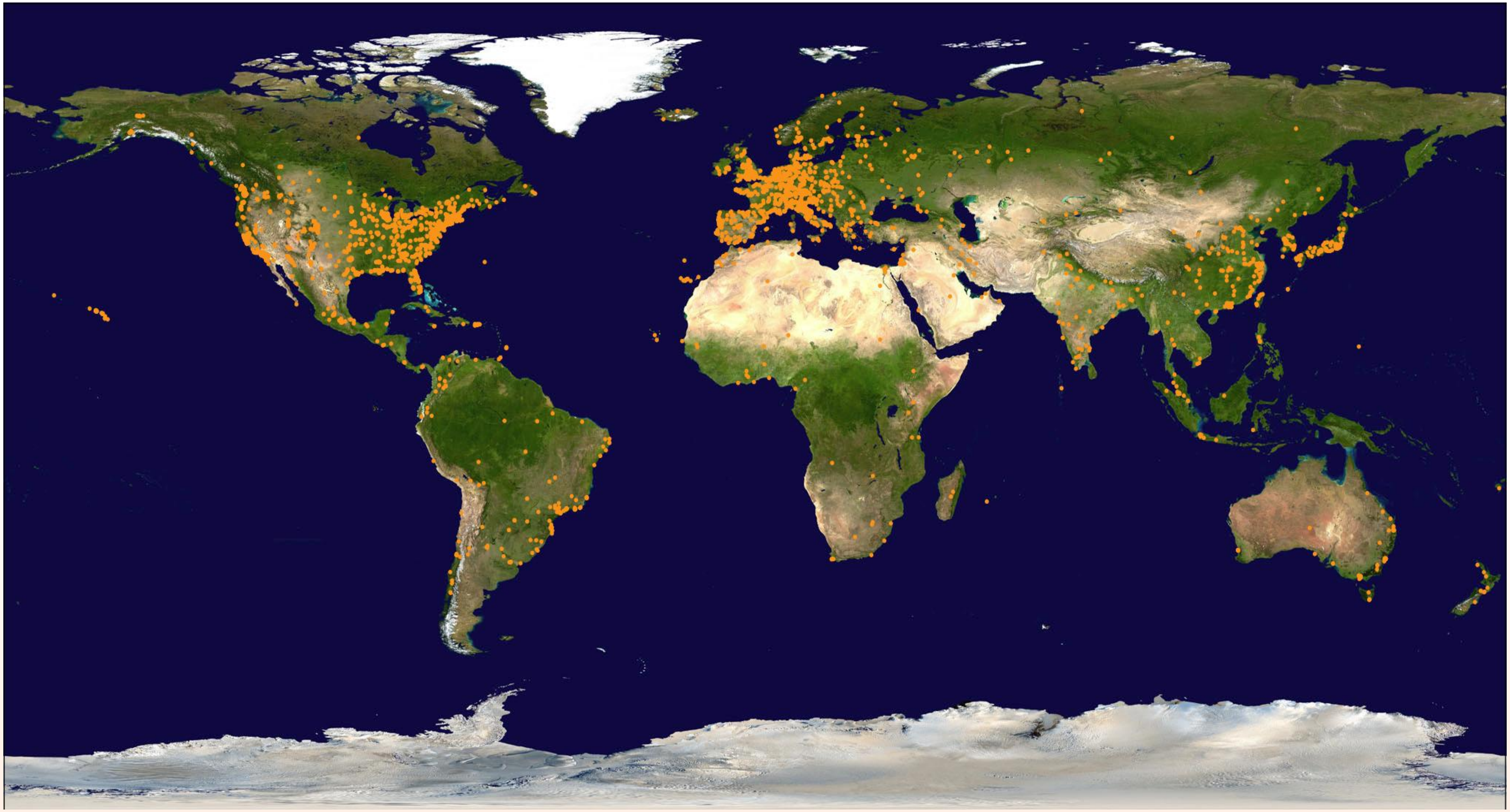
- 0.25°, 0.5°, 1°, 2°, T31 resolution
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~1.5 million lines of computer code

CESM - A Community Resource

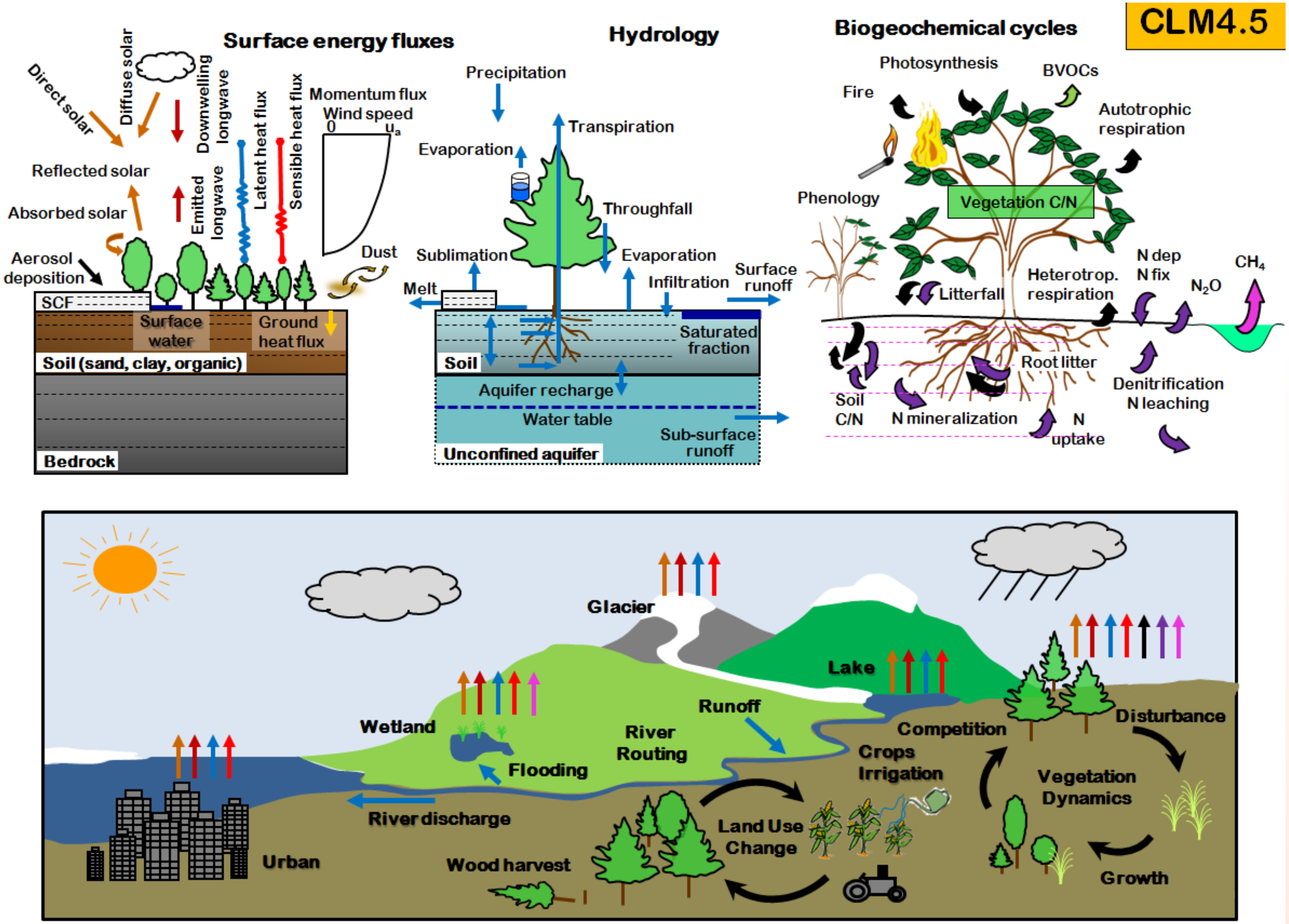


Courtesy Gary Strand

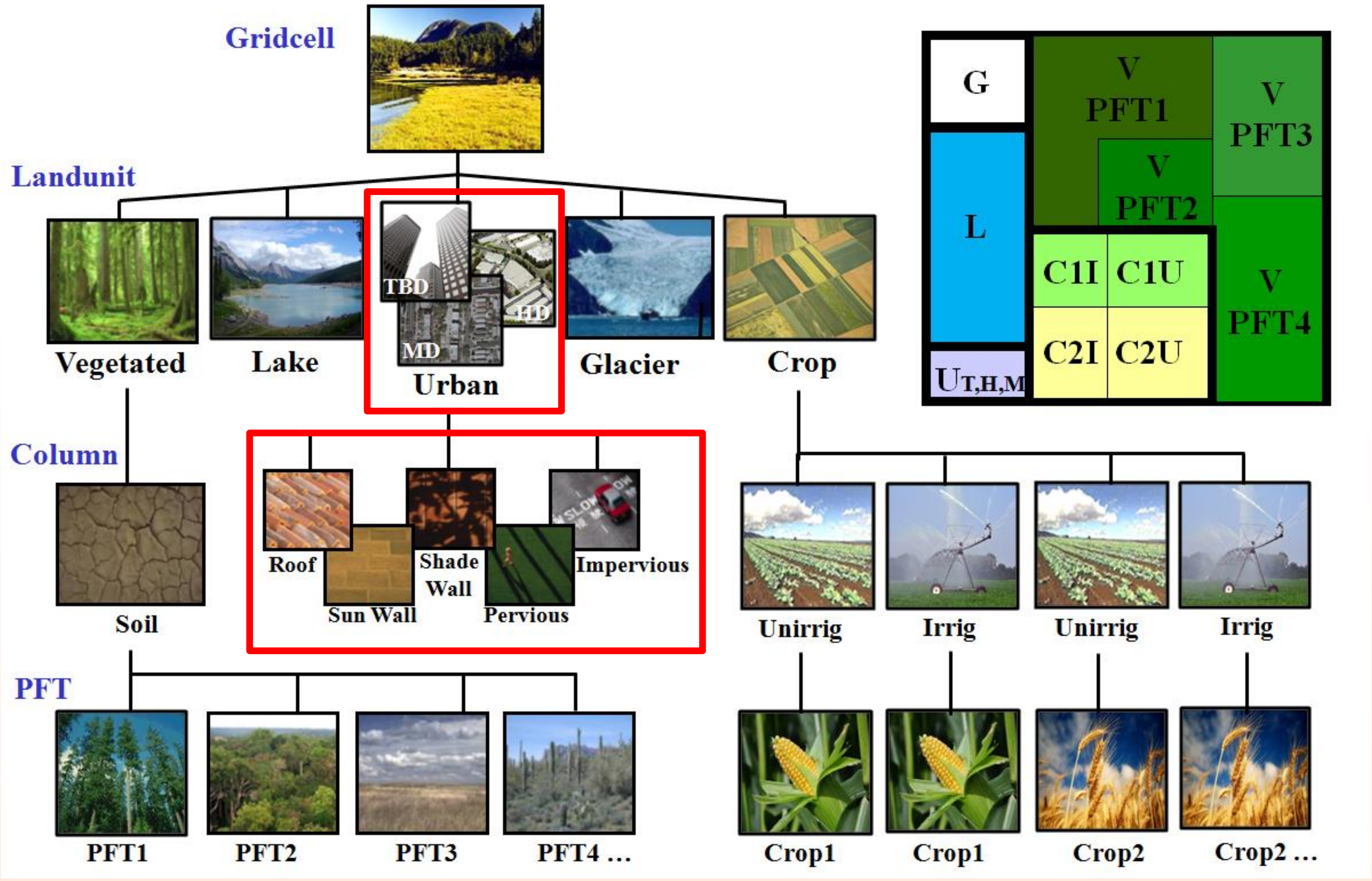
>1500 Registered Users of CESM1.0

>2.4 PB of model data downloaded since January 2008

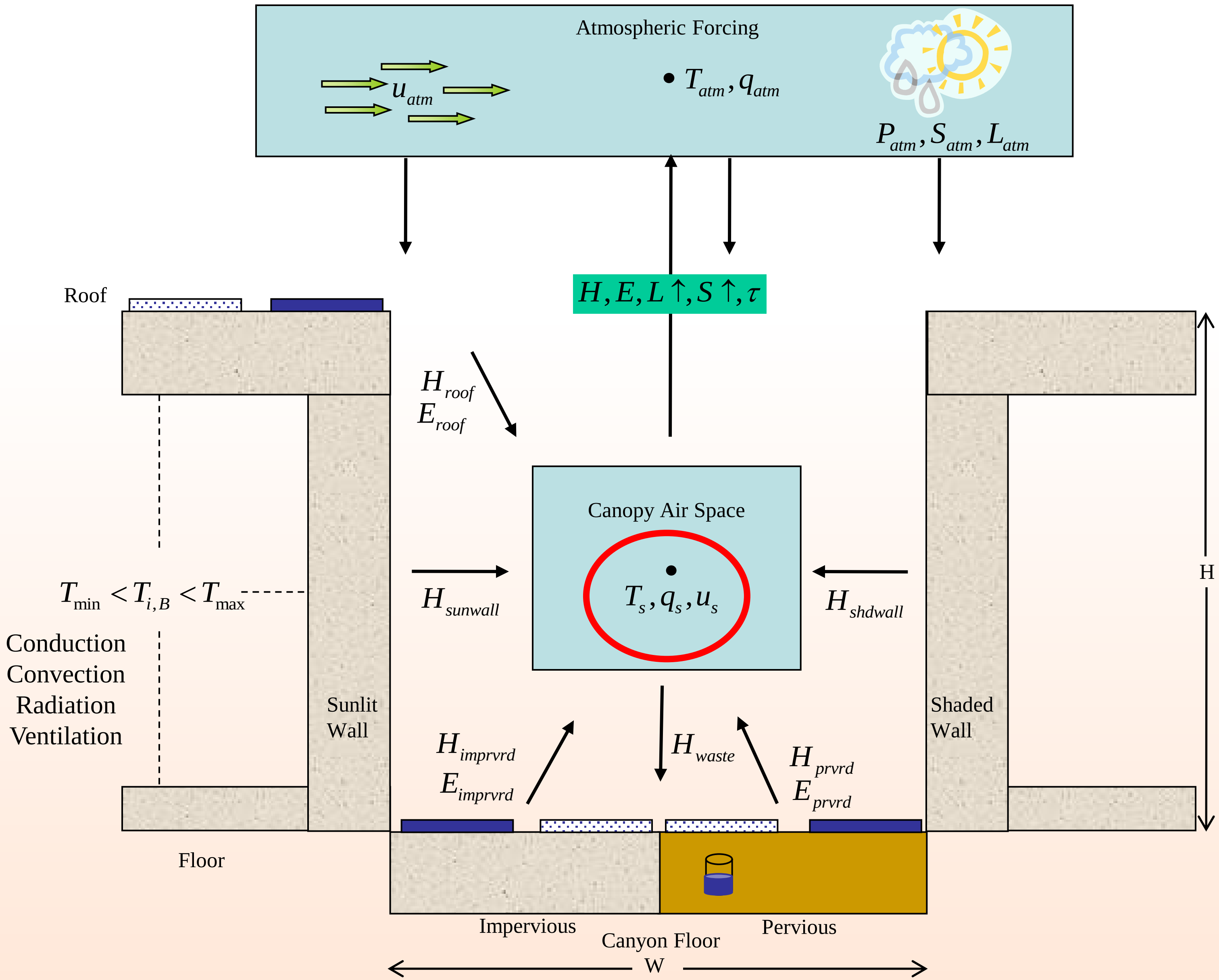
Community Land Model (CLM)



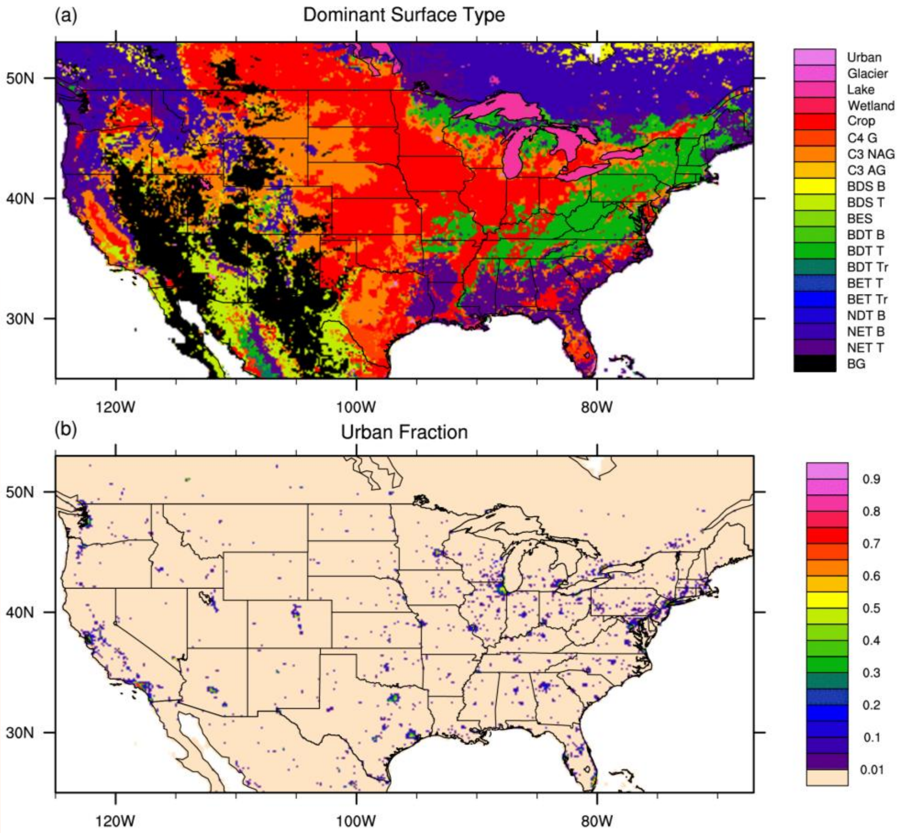
Incorporating Urban Areas into CLM



Community Land Model Urban (CLMU)



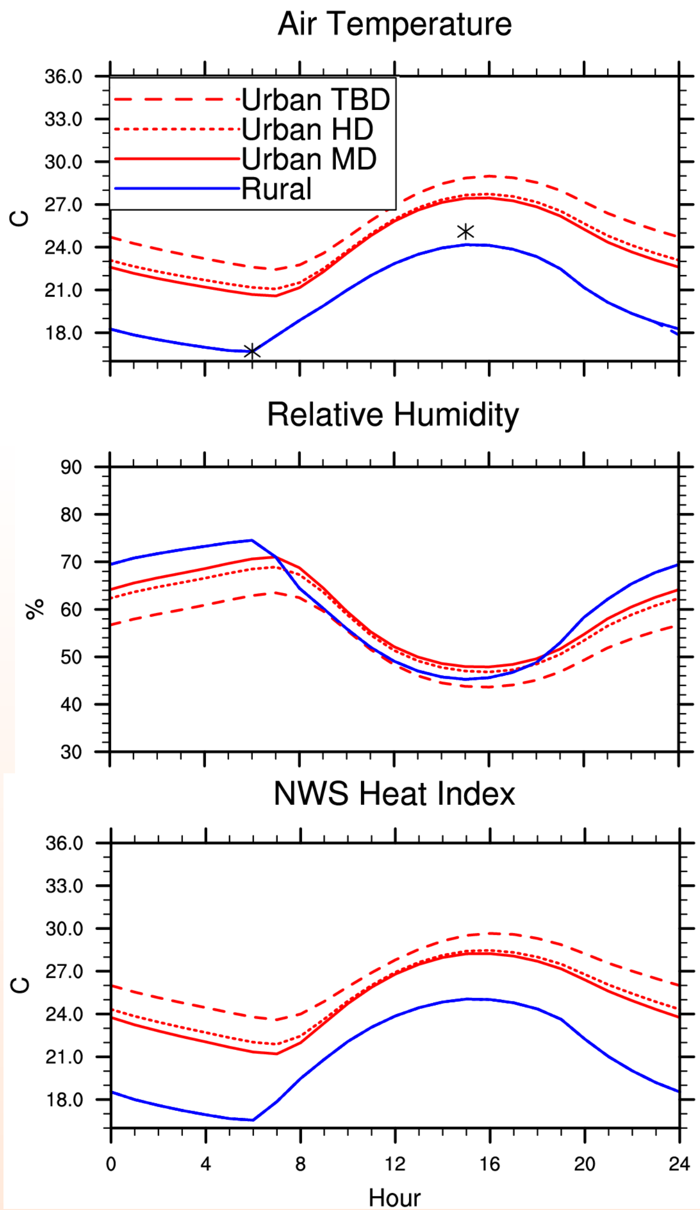
SIMMER – Exploring interactions between urbanization, heat stress (HS), and climate change



- Investigate present-day and projected mid-21st century rural and urban summer HS and examine the effects of idealized urban density types (medium, high, and tall building district) on HS
- WRF used to downscale a CESM 20th century and a IPCC AR5 RCP8.5 ensemble member to provide a consistent set of atmospheric forcing variables (CLM run in offline mode)
- 1/8th degree simulations for 1986-2005 and 2046-2065
- HS assessed using T alone but also heat indices
  - NWS Heat Index (T, RH)
  - Apparent Temperature (T, VP, U)
  - Simplified Wet Bulb Globe Temperature (T, VP)
  - Humidex (T, VP)
  - Discomfort Index (T,RH)
- Heat indices calculated online for rural and urban surfaces

Oleson et al. 2013, Climatic Change

JJA 1986-2005 Toronto (43.4-43.9N, 280.4-280.9E)



- The UHI effect increases with increases in urban density (nighttime UHI is 4.3°C, 4.8°C, 6.5°C for MD, HD, and TBD)

- Despite lower urban humidity at night, UHI as indicated by the Heat Index is larger than for temperature alone (nighttime Heat Index UHI is 5.2°C, 5.8°C, and 7.5°C for MD, HD, and TBD)

Medium density (MD); High Density (HD); Tall Building District (TBD)

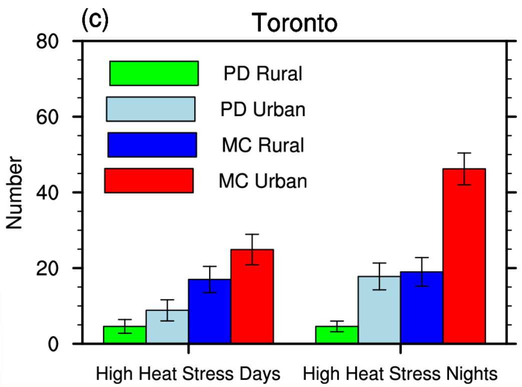
* Climatological (1971-2000) daily Tmax/Tmin from Environment Canada weather station (WMO 71266)

Oleson et al. 2013, Climatic Change

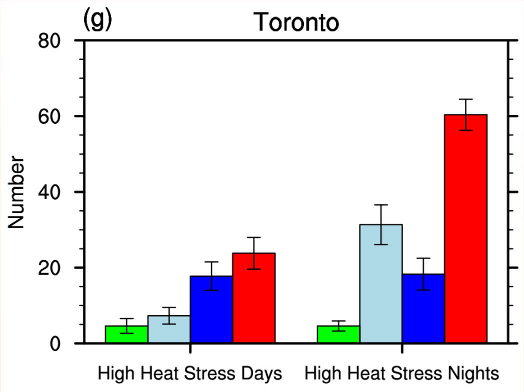
High Heat Stress Days and Nights - Toronto

Number of days per summer with min and max exceeding the RURAL min95 and max95 for 1986-2005

Air Temperature



NWS Heat Index (HI)



	Tmax95	Tmin95	HImax95	HImin95
°C (F)	33 (91)	23 (73)	35 (95)	24 (75)

Present-day (PD)

- High heat stress days and nights occur more frequently in urban than rural areas and more frequently at night (e.g., urban has 9 days with Tmax above 33°C but 18 nights with Tmin above 23°C)

Mid-century (MC)

- As indicated by temperature alone, climate change increases the number of high heat stress days and nights in both rural and urban areas (i.e., rural has 12 and 13 more high heat stress days and nights; urban has 16 and 28 more high heat stress days and nights).

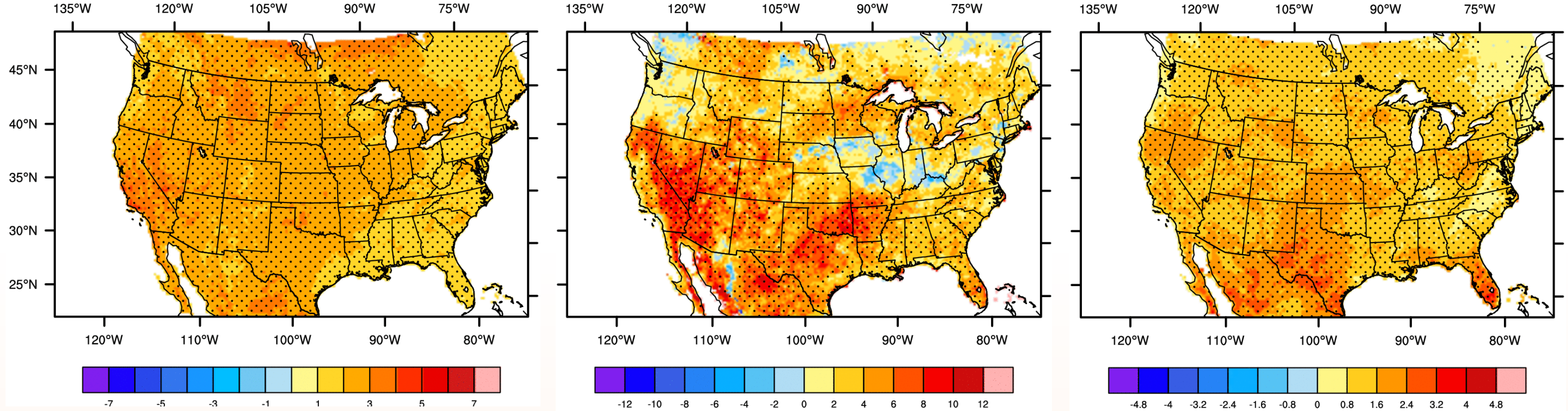
- Urban high heat stress nights are amplified for the NWS HI compared to temperature alone (urban has 46 nights as defined by air temperature and 60 as defined by NWS HI).

Oleson et al. 2013, Climatic Change

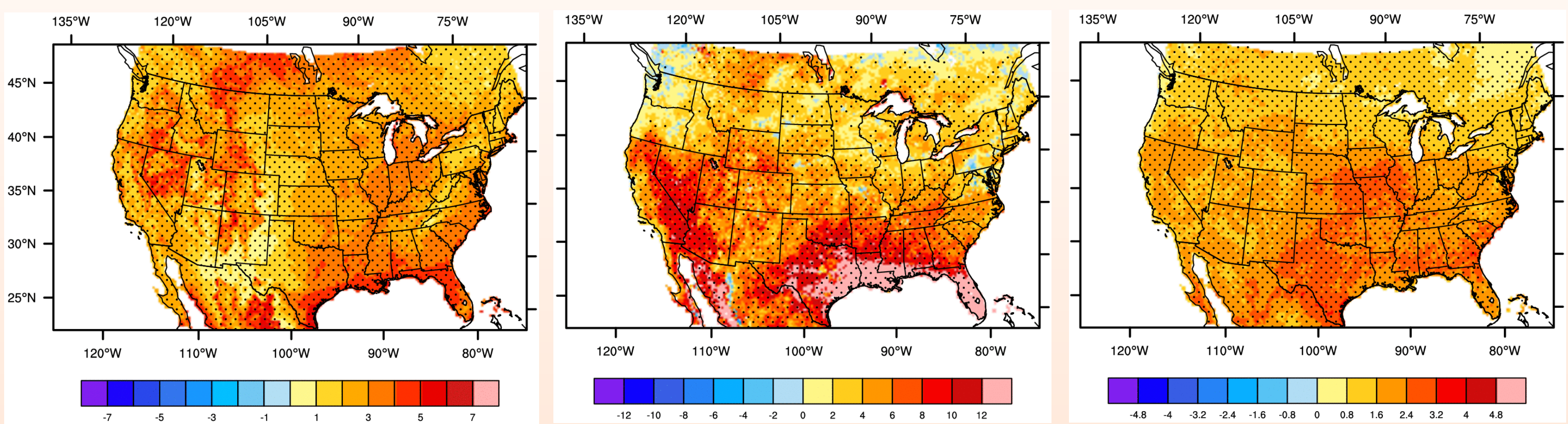
2046-2065 – 1986-2005 JJA Rural Heatwaves

Air Temperature

Intensity (°C) | Duration (days/event) | Frequency (events/JJA)



NWS Heat Index



Heatwaves defined following Meehl and Tebaldi (2004) and Gao et al. (2012).

Average number of summer days in each heat stress index category
Daily Maximum
Medium Density Urban Toronto

NWS Heat Index (Smith et al. 2013)

Category	Caution	Extreme Caution	Danger	Extreme Danger
Threshold	> 80°F (26.7°C)	>90°F (32.2°C)	>105°F (40.6°C)	>130°F (54.4°C)
Present-day Urban	48.4	19.4	0.4	0.0
Mid-century Urban	37.9	29.3	4.8	0.0

Humidex (Masterson and Richardson 1979)

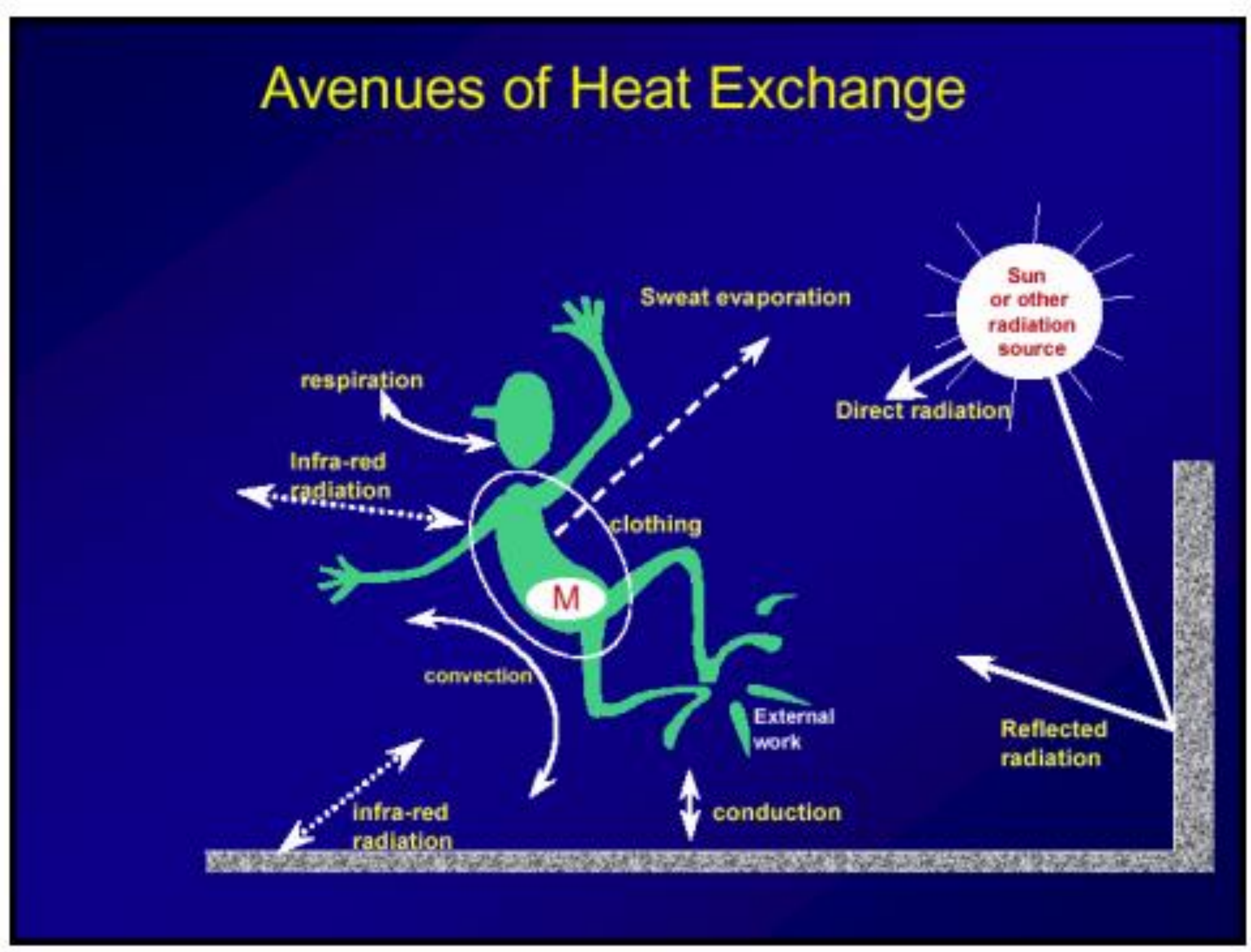
Category	Some Discomfort	Great Discomfort	Dangerous	Imminent Heat Stroke
Threshold	□30°C	□40°C	□46°C	□54°C
Present-day Urban	57.6	8.8	0.3	0.0
Mid-century Urban	53.7	24.8	2.4	0.0

Discomfort Index (Epstein and Moran 2006)

Category	No Heat Stress	Mild Sensation of Heat	Moderately Heavy Heat Load	Severe Heat Load
Threshold	< 22 units	□ 22 units	>24 units	> 28 units
Present-day Urban	20.3	18.4	42.2	11.2
Mid-century Urban	8.5	10.6	42.2	30.8

Oleson et al. 2013, Climatic Change

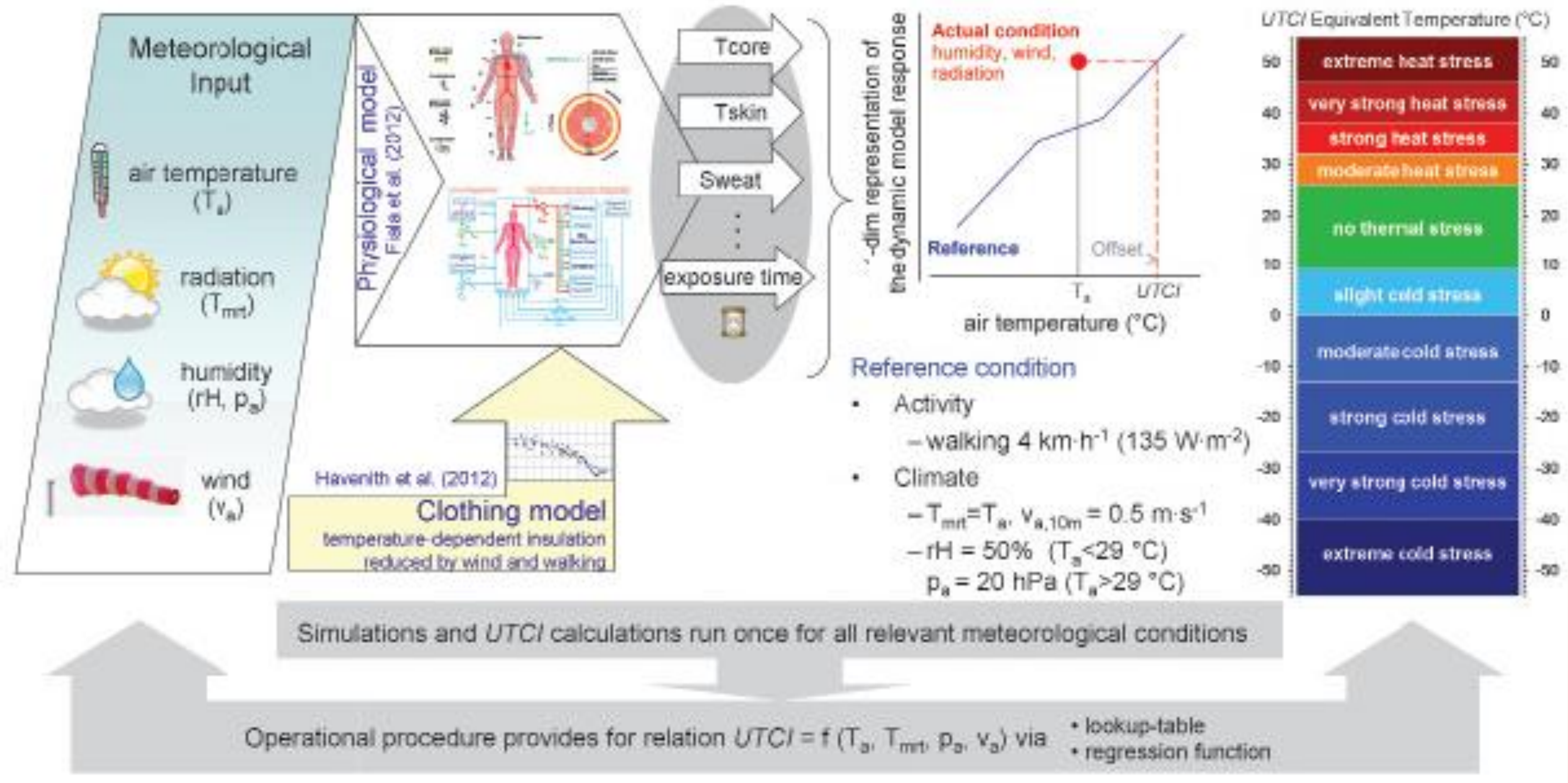
Human thermal comfort depends on environmental and behavioral factors – energy balance



Havenith 2003

Future Work - Humans in CESM/CLM

Universal Thermal Climate Index (UTCI; utci.org)



Bröde et al. 2013

➢ Thermal strain index calculated by PCA as a one-dimensional representation of the multi-dimensional dynamic response of the physiological model.
➢ UTCI equivalent temperature for given combination of wind, radiation, humidity and air temperature is defined as the air temperature in the reference environment, which produces the same strain index value.

Conclusions

- Urban areas should be modeled explicitly in climate models given that urban climate is quite different from rural climate and more than half of the world's population lives in urban areas.

- Climate models should consider other aspects of heat stress other than just temperature.

- Furthermore, we need to move beyond simple diagnostic heat stress indices and consider more state-of-the-art indicators of heat stress that have close relationships with the physiological response of humans.

Thank You

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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.

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Caveats and Limitations

- Complexity of cities reduced to three urban landunits
  - Inadequacies of the urban canyon model in representing complex urban surfaces both within a city and between cities
- 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/global climate (minimal feedbacks)
- Future urban form and function
  - Also not addressed are 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
- Energy demand
  - The heating, air conditioning, and wasteheat fluxes in the model are highly simplified representations of these processes (ignore windows, building ventilation, diversity of HAC systems). We also ignore 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.

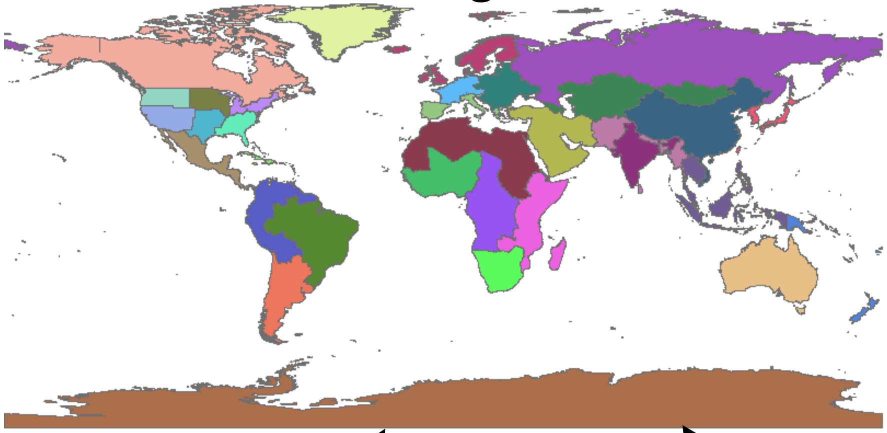
CLMU Publications

- 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.

Urban Data

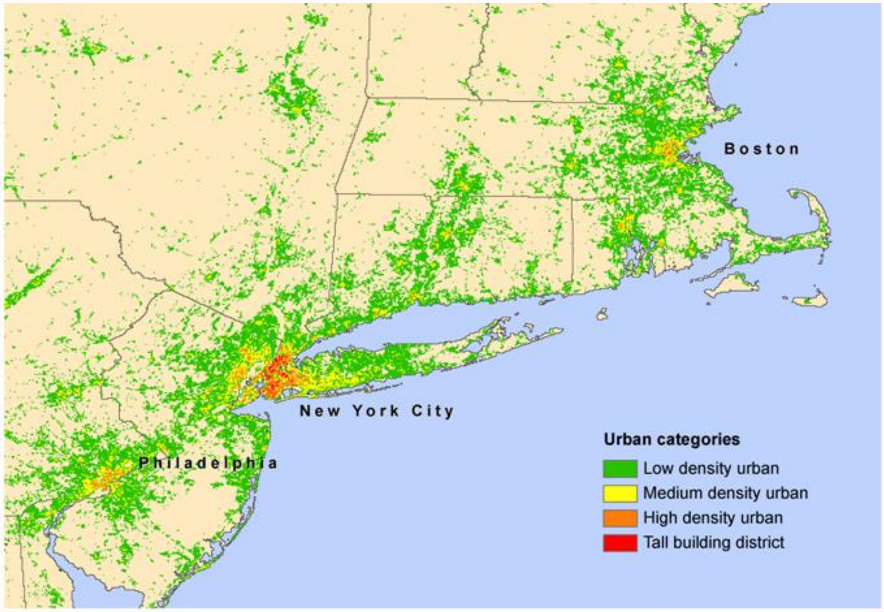
Global Urban Characteristics Dataset

Global Regions



To CLMU

Urban Extent - Landscan 2004



T. Jackson, J. Feddema, 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***

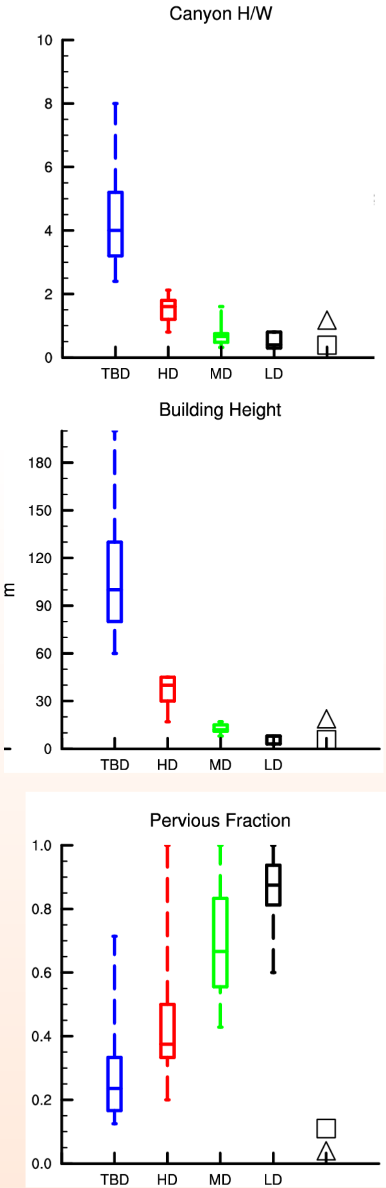
Thermal – Roof/Wall/Road

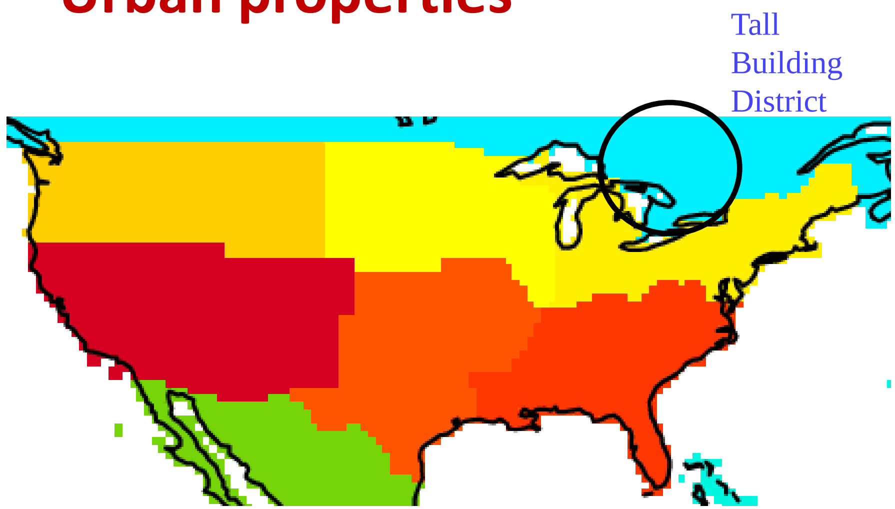
- ***Conductivity***
- ***Heat Capacity***

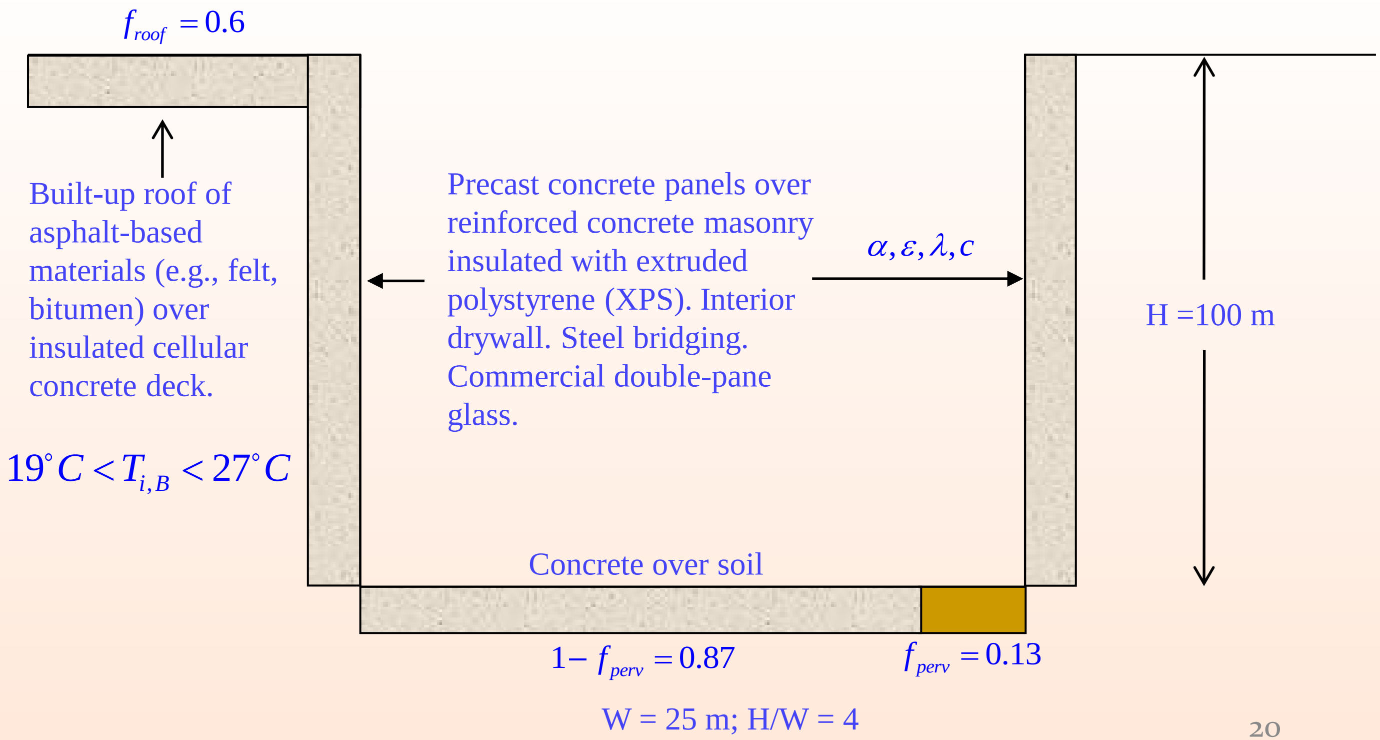
Interior temperature settings (HAC)

Urban properties

Global

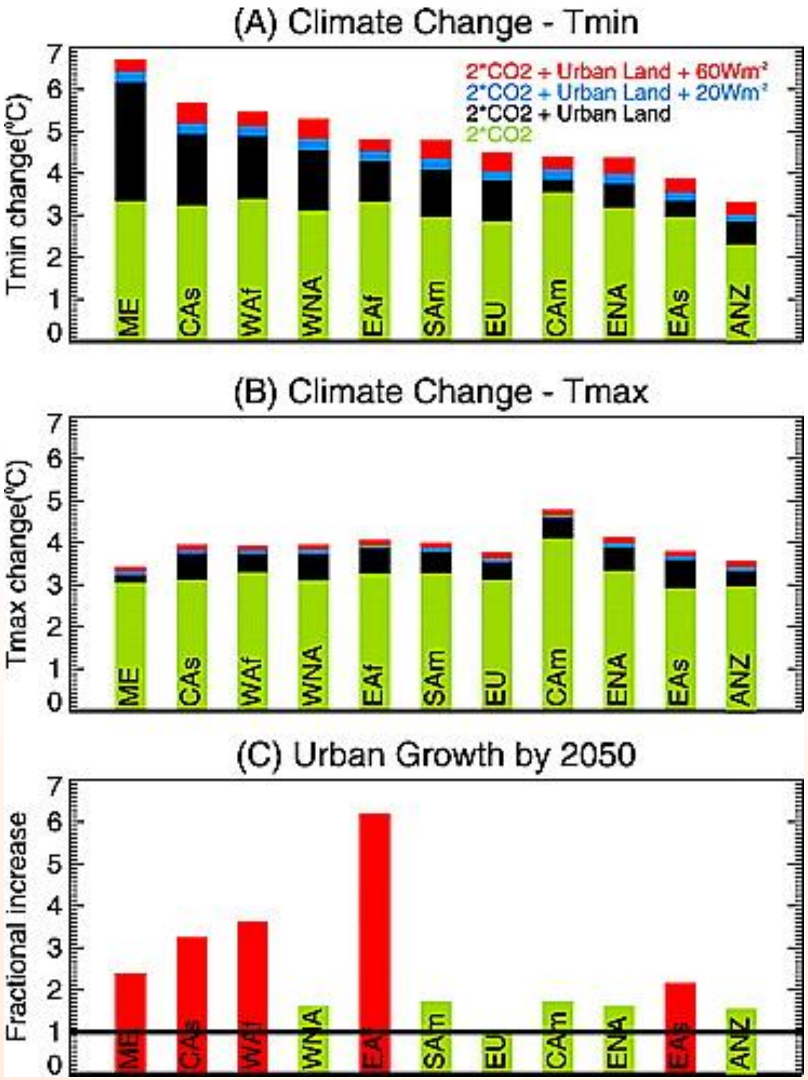






Global Results

Why represent urban areas in a climate model?



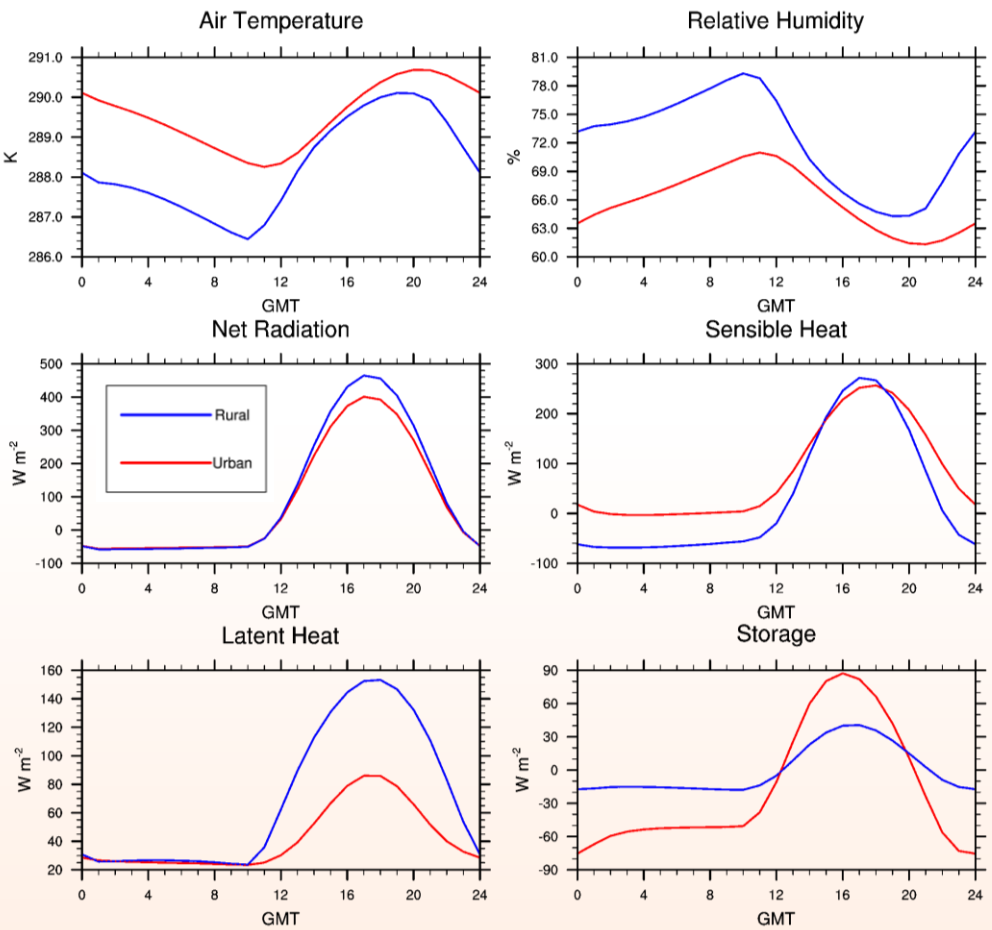
McCarthy et al. 2010

- 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.

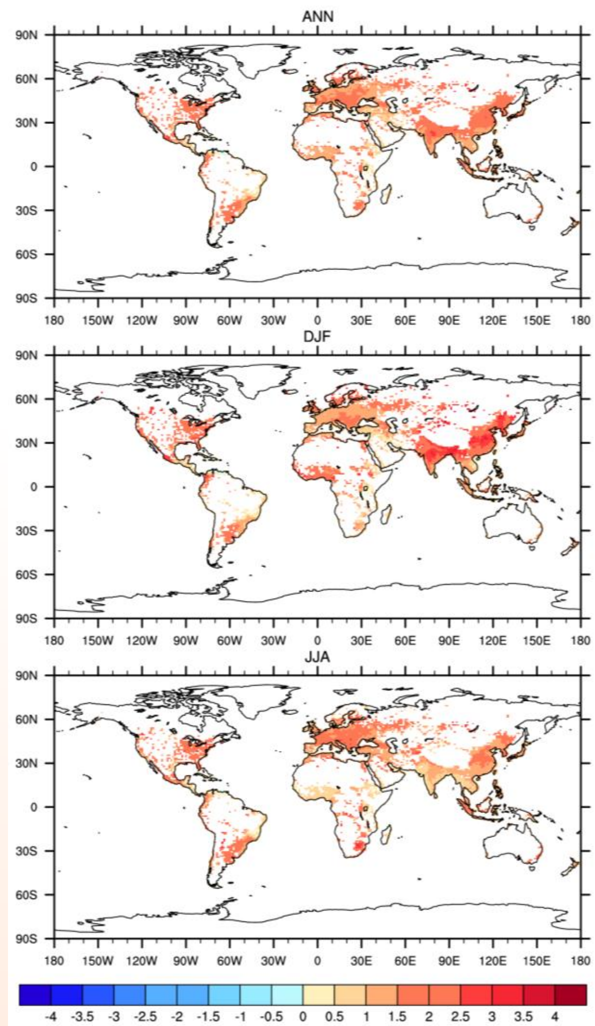
ME (Middle East); CAs (Central Asia); WAf (West Africa); WNA (Western North America); EAf (East Africa); SAm (South America); EU (Europe); CAm (Central America); ENA (Eastern North America); EAs (Eastern Asia); ANZ (Australia/New Zealand)

Present Day Urban Energy Balance and Heat Island

Annual Average Diurnal Cycle



Average Heat Island (°C)



ANN

DJF

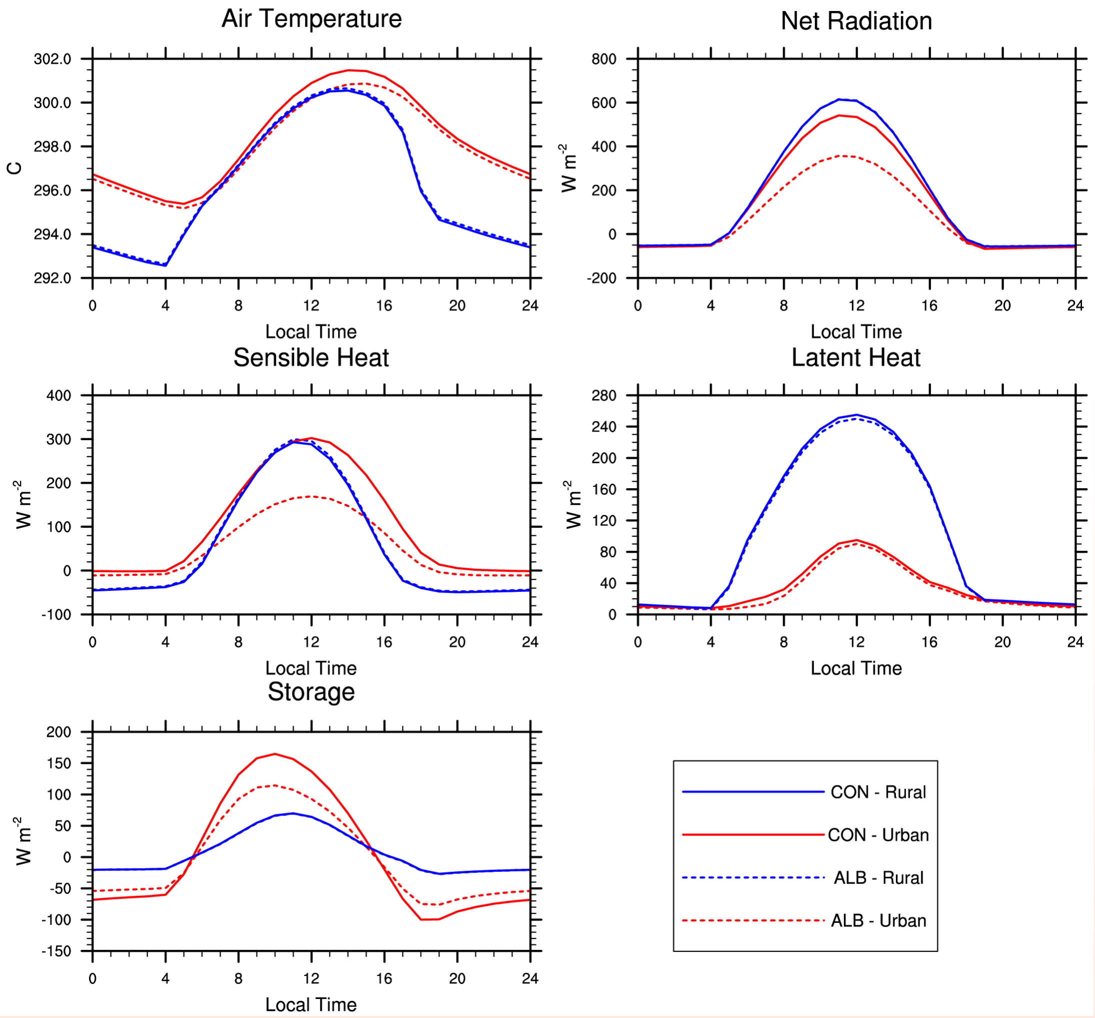
JJA

- 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

- 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

Mitigation – White Roofs

JJA average diurnal cycle
40.7N, 287.5E



Urban compared to Rural in the control simulation (CON: solid red/blue lines):

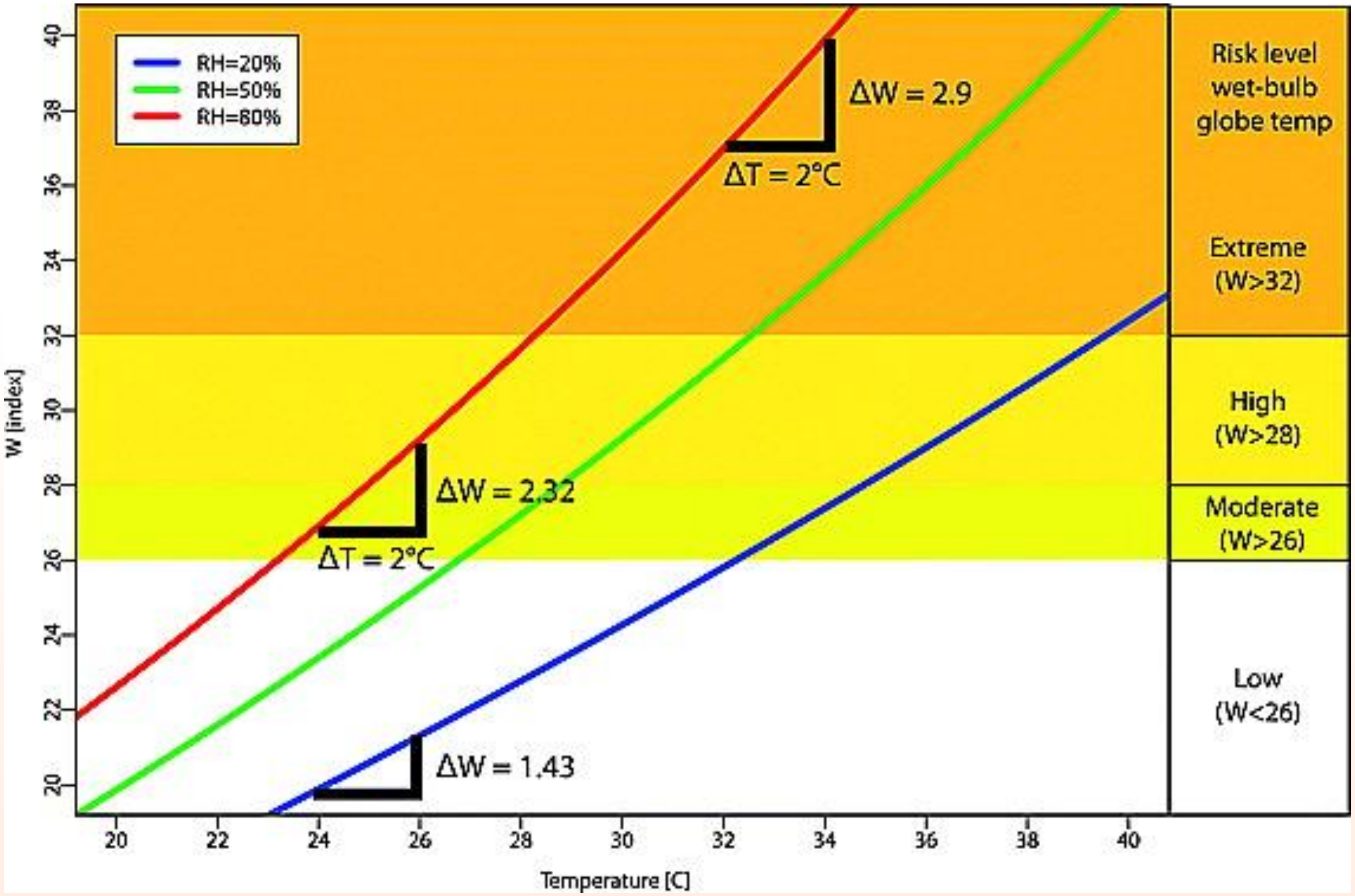
- Available energy partitioned into more storage and less latent heat
- Stored heat released at night
- Warmer urban temperatures, particularly at night

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)

Urban and rural heat stress response to climate change

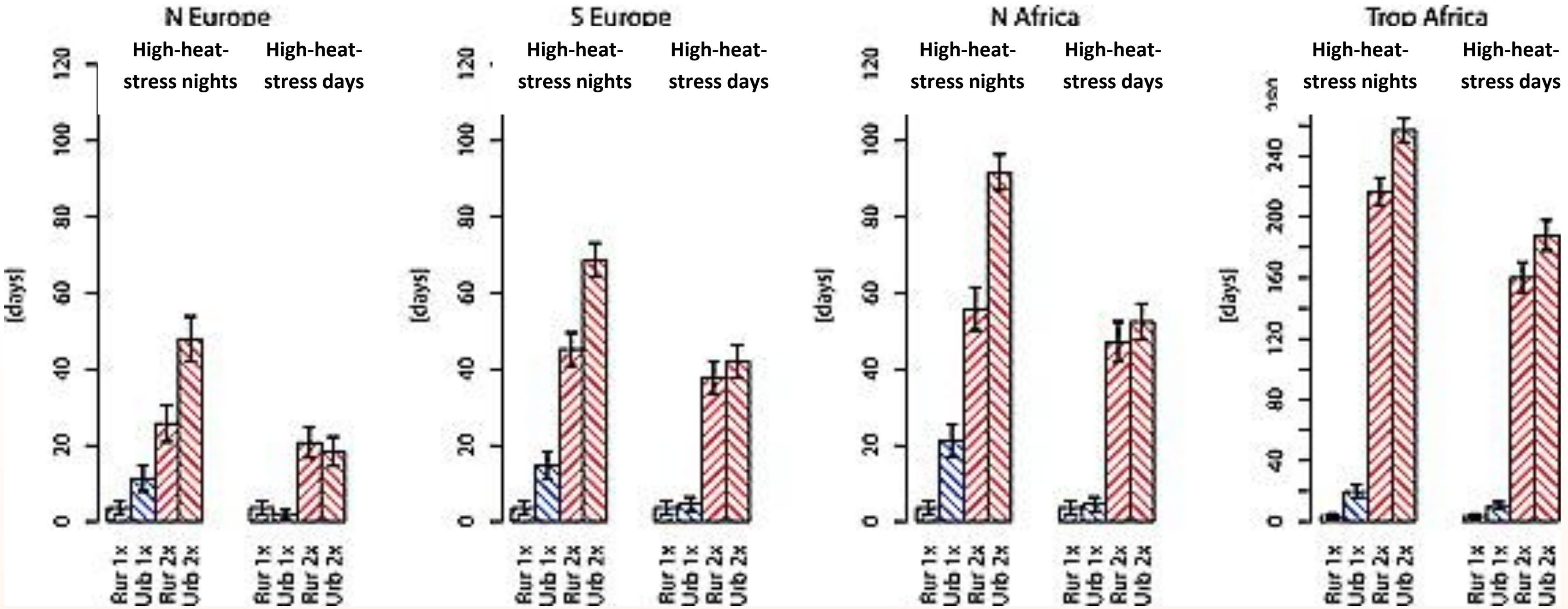
Simplified Wet-bulb Globe Temperature : W = 0.567T+0.393e+3.94
(Willett and Sherwood 2011)



A 2°C warming yields larger W increases if humidity is high and/or temperature is high

Fischer, E.M., K.W. Oleson, and D.M. Lawrence, 2012: Contrasting urban and rural heat stress responses to climate change. GRL, 39, doi10.1029/2011GL050576.

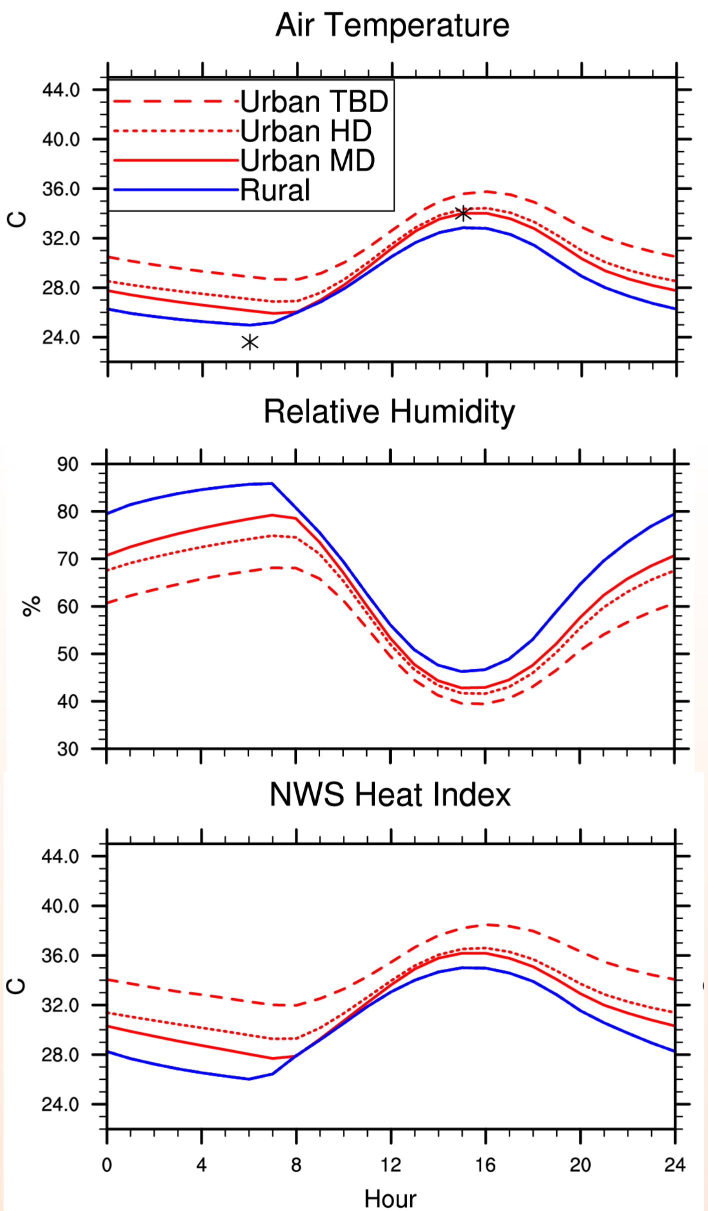
Frequency of rural and urban high-heat-stress nights and days at 1xCO2 and 2xCO2: Number of days per year with Wmin and Wmax exceeding the present-day rural $Wmin99_{1xCO2}$ and $Wmax99_{1xCO2}$



- At 1xCO2, high-heat-stress nights are substantially higher in urban areas
- 2xCO2 leads to substantially more high-heat-stress nights and days
- Despite similar urban-rural response of W to 2xCO2, the frequency increase of urban high-heat-stress nights can substantially exceed that in rural areas, a consequence of the non-linearity in the exceedance frequency.
- Despite weaker overall warming in tropical Africa, occurrence of high-heat-stress nights and days increases strongly, a consequence of small temperature seasonal cycle and low synoptic variability.

More SIMMER Results

JJA 1986-2005 Houston (29.52-30.02N, 264.4-264.9E)



- The UHI effect increases with increases in urban density (nighttime UHI is 0.9°C, 1.9°C, 3.7°C for MD, HD, and TBD)
- The urban relative humidity is lower than rural, particularly at night
- Despite lower urban humidity, UHI as indicated by the Heat Index is larger than for temperature alone, particularly at night when humidity is high (nighttime Heat Index UHI is 1.7°C, 3.3°C, and 6.0°C for MD, HD, and TBD)

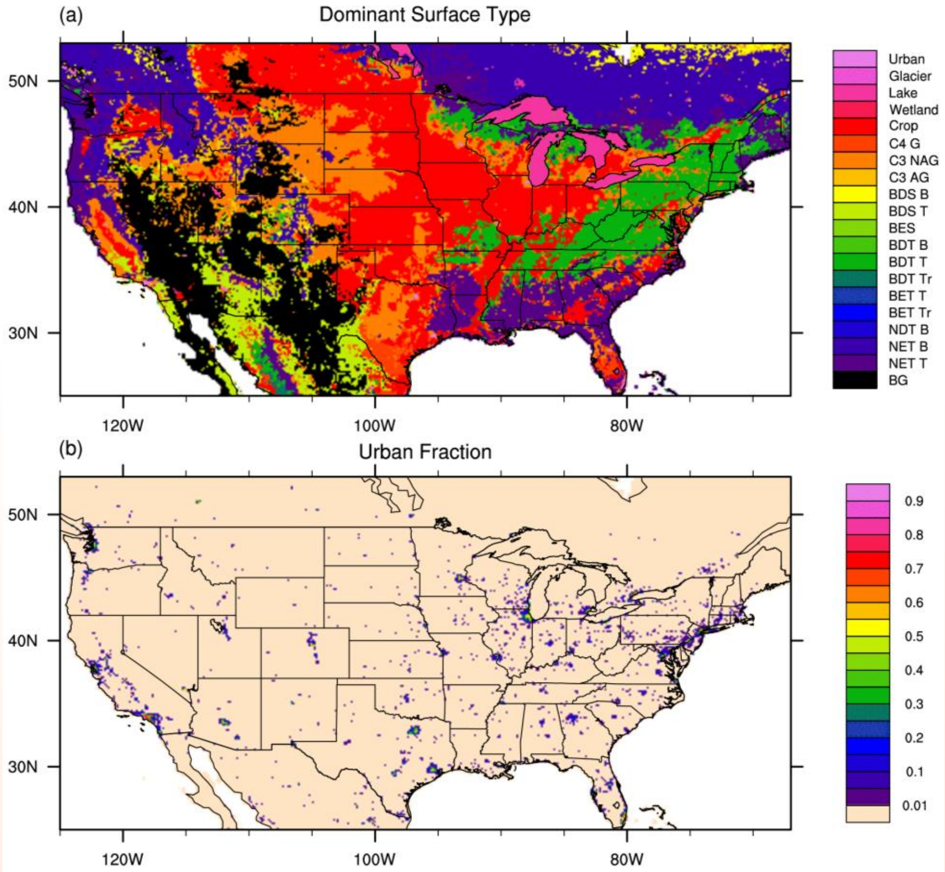
Medium density (MD); High Density (HD); Tall Building District (TBD)

* Climatological (1981-2010) daily Tmax/Tmin from weather station at Houston Bush Intercontinental Airport (GHCND:USW00012960; NOAA NCDC 2012)

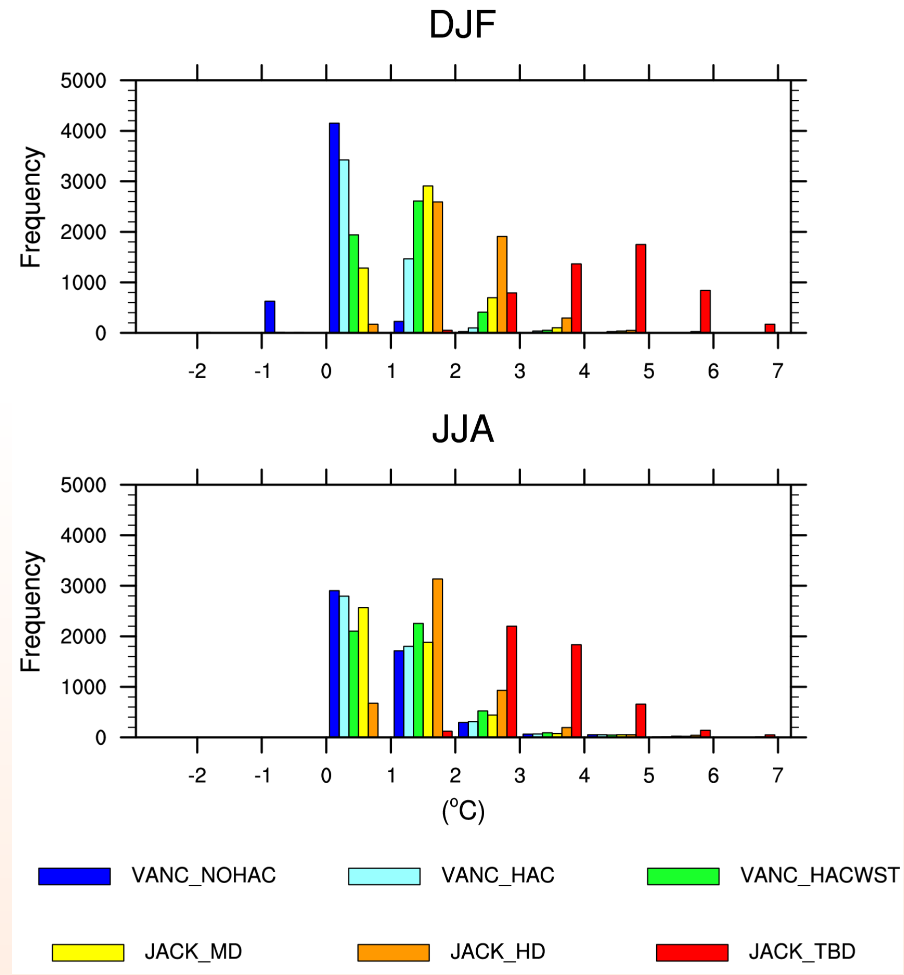
Oleson et al. 2013, Climatic Change

Effects of Urban Density and AHF on UHI

CLM forced by NLDAS (1990-2009)



Urban – Rural MIN Air Temp



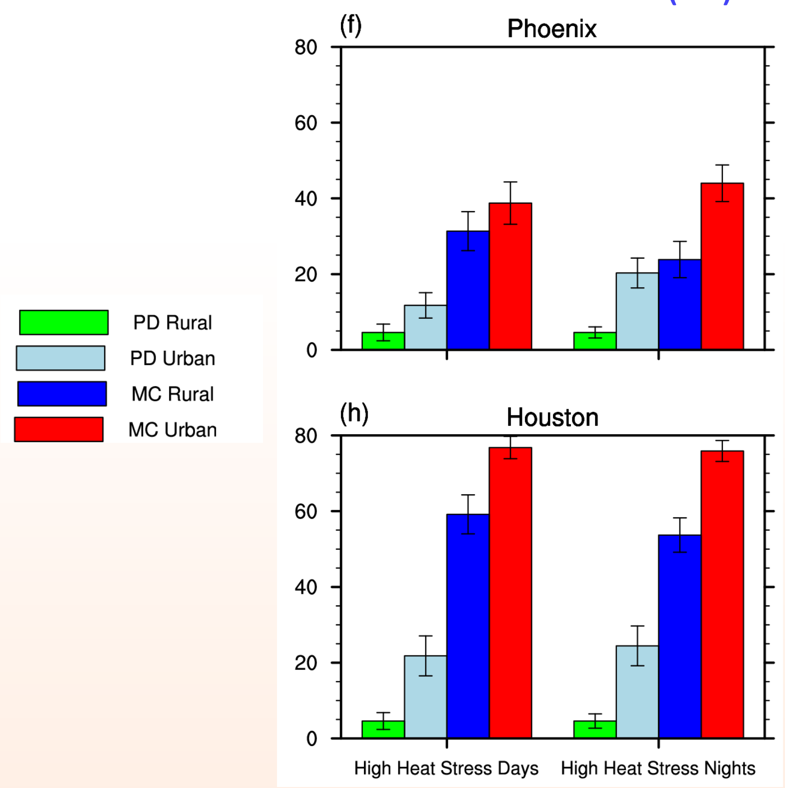
Average Urban – Rural MIN Air Temp (°C)

	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

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

NWS Heat Index (HI)



	HImax95 [°C(F)]	HImin95 [°C(F)]
Phoenix	42 (108)	30 (86)
Houston	38 (100)	30 (86)

Present-day

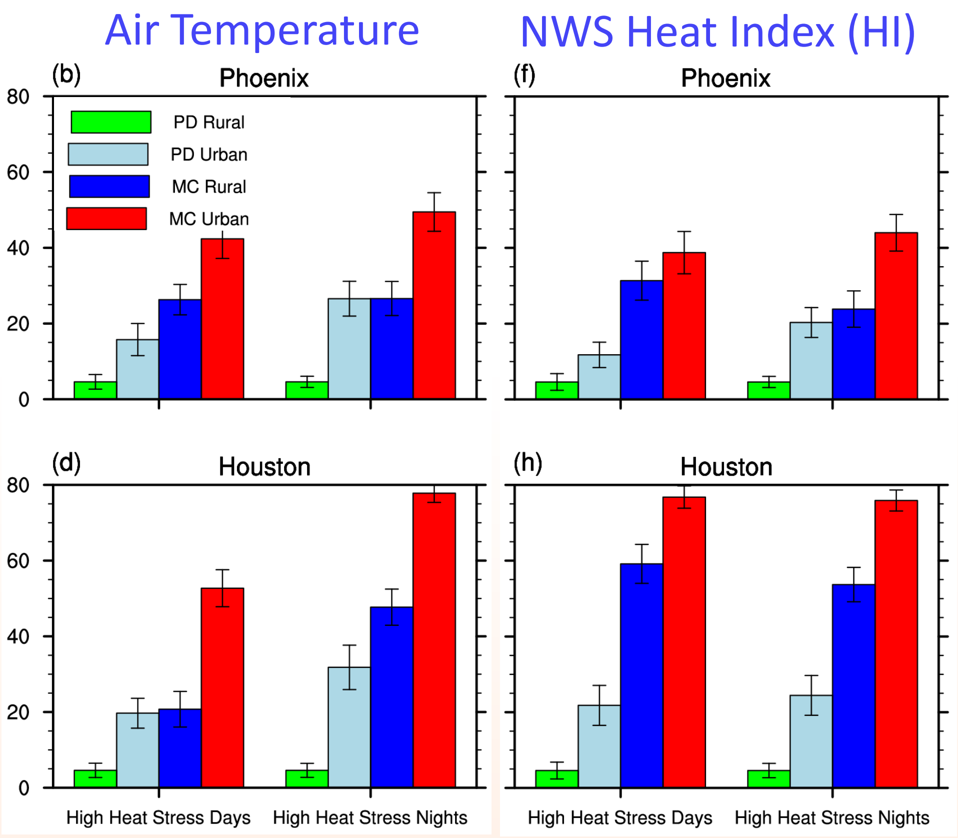
- High heat stress days and nights occur more frequently in urban than rural areas
- Urban high heat stress occurs more frequently at night (e.g., urban Phoenix has 20 nights with HImin above 30°C and 12 days with HImax above 42°C)

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).

Oleson et al. 2013, Climatic Change

Present-day and Mid-century High Heat Stress (HHS) Days and Nights



°C (°F)	Tmax95	Tmin95	HImax95	HImin95
Phoenix	45 (113)	31 (88)	42 (108)	30 (86)
Houston	37 (99)	27 (81)	38 (100)	30 (86)

- HHS days and nights occur more frequently in urban than rural areas
- Urban/rural contrast in heat stress is more pronounced at night (e.g., urban Phoenix has 27 nights with Tmin above 31°C and 15 days with Tmax above 45°C)
- Climate change significantly increases the number of HHS days and nights in both rural and urban areas, particularly in Houston (e.g., rural Houston has 21 days above 37°C and 48 nights above 27°C; urban Houston has 53 days above 37°C and 78 nights above 27°C).
- HHS days and nights defined from the NWS Heat Index differs from that using temperature alone:
  - In Phoenix, number of urban HHS days/nights decreases from 16/26 to 12/20
  - In Houston, urban HHS days for Houston increase from 53 to 77 days.

Oleson et al. 2013, Climatic Change, in press.

Average number of summer days in each heat stress index category - Toronto

PD: Present-day, MC: Mid-century

2-m Air Temperature (Smith et al. 2013)

Category	----	Hot	Very Hot	Extremely Hot
Threshold	----	> 85th percentile PD Rural	> 90th percentile PD Rural	> 95th percentile PD Rural
PD Urban	----	6.5	6.3	8.9
MC Urban	----	8.2	10.3	24.9

Apparent Temperature (Smith et al. 2013)

Category	----	Hot	Very Hot	Extremely Hot
Threshold	----	> 85th percentile PD Rural	> 90th percentile PD Rural	> 95th percentile PD Rural
PD Urban	----	6.1	7.9	8.9
MC Urban	----	7.9	10.7	28.9

NWS Heat Index (Smith et al. 2013)

Category	Caution	Extreme Caution	Danger	Extreme Danger
Threshold	> 80°F (26.7°C)	>90°F (32.2°C)	>105°F (40.6°C)	>130°F (54.4°C)
PD Urban	48.4	19.4	0.4	0.0
MC Urban	37.9	29.3	4.8	0.0

Humidex (Masterson and Richardson 1979)

Category	Some Discomfort	Great Discomfort	Dangerous	Imminent Heat Stroke
Threshold	□30°C	□40°C	□46°C	□54°C
PD Urban	57.6	8.8	0.3	0.0
MC Urban	53.7	24.8	2.4	0.0

Simplified Wet Bulb Globe Temperature (Willett and Sherwood 2012)

Category	----	High	Very High	Extreme
Threshold	----	>28°C	>32°C	>35°C
PD Urban	----	34.2	6.7	0.4
MC Urban	----	39.5	20.2	3.1

Discomfort Index (Epstein and Moran 2006)

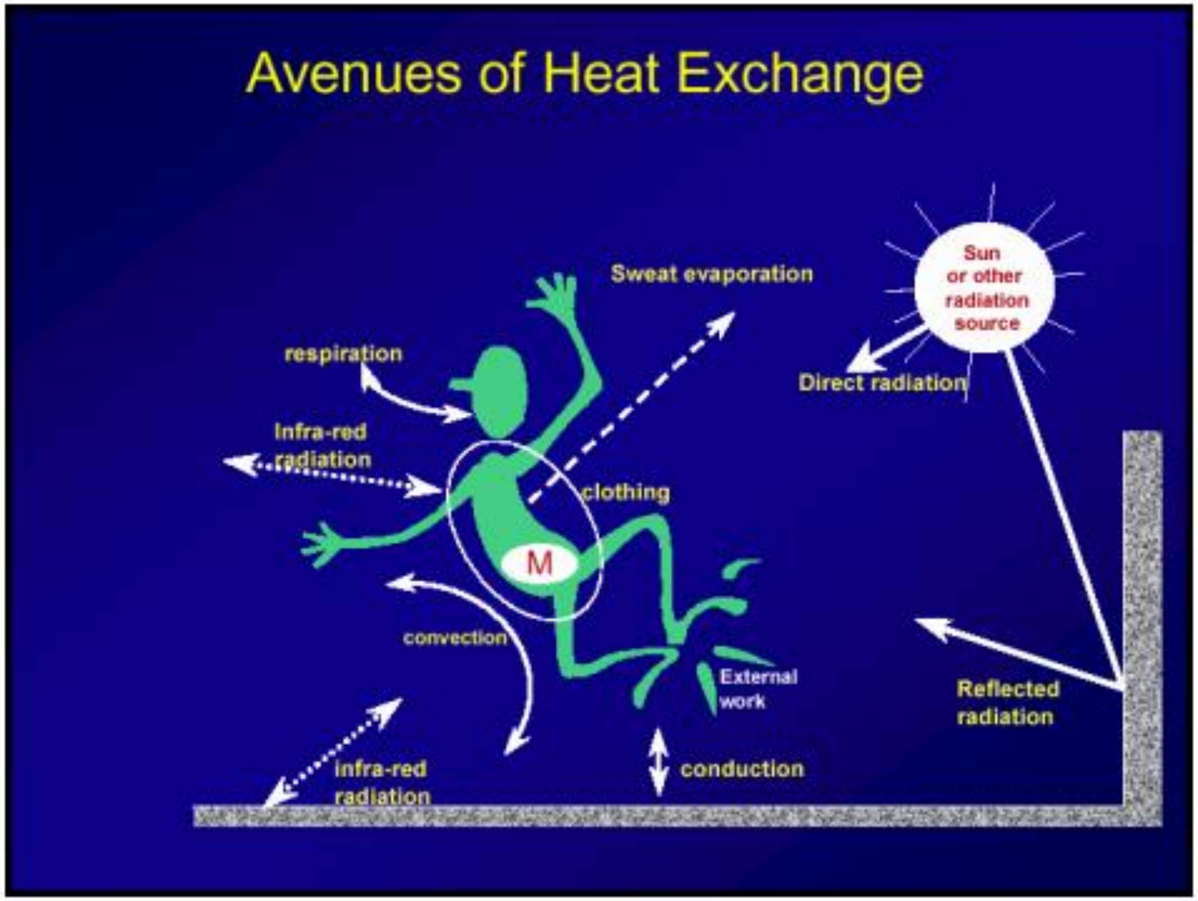
Category	No Heat Stress	Mild Sensation of Heat	Moderately Heavy Heat Load	Severe Heat Load
Threshold	< 22 units	□ 22 units	>24 units	> 28 units
PD Urban	20.3	18.4	42.2	11.2
MC Urban	8.5	10.6	42.2	30.8

Oleson et al. 2013, Climatic Change

Average number of summer days in each heat stress index category - Houston

	2-m Air Temperature (Smith et al. 2013)			
Category	----	**Hot**	**Very Hot**	**Extremely Hot**
Threshold	----	**> 85th percentile**	**> 90th percentile**	**> 95th percentile**
PD Urban	----	**7.3**	**11.6**	**19.7**
MC Urban	----	**5.4**	**10.8**	**52.7**
	Apparent Temperature (Smith et al. 2013)			
Category	----	**Hot**	**Very Hot**	**Extremely Hot**
Threshold	----	**> 85th percentile**	**> 90th percentile**	**> 95th percentile**
PD Urban	----	**8.0**	**11.8**	**22.2**
MC Urban	----	**3.9**	**6.6**	**70.6**
	NWS Heat Index (Smith et al. 2013)			
Category	**Caution**	**Extreme Caution**	**Danger**	**Extreme Danger**
Threshold	**> 80°F (26.7°C)**	**>90°F (32.2°C)**	**>105°F (40.6°C)**	**>130°F (54.4°C)**
PD Urban	**4.8**	**81.6**	**5.3**	**0.0**
MC Urban	**1.2**	**38.4**	**52.1**	**1 day/4 years**
	Humidex (Masterson and Richardson 1979)			
Category	**Some Discomfort**	**Great Discomfort**	**Dangerous**	**Imminent Heat Stroke**
Threshold	**□30°C**	**□40°C**	**□46°C**	**□54°C**
PD Urban	**15.8**	**73.2**	**2.5**	**0.0**
MC Urban	**4.0**	**60.3**	**27.4**	**1 day/5 years**
	Simplified Wet Bulb Globe Temperature (Willett and Sherwood 2012)			
Category	----	**High**	**Very High**	**Extreme**
Threshold	----	**>28°C**	**>32°C**	**>35°C**
PD Urban	----	**23.2**	**61.8**	**3.9**
MC Urban	----	**4.8**	**52.5**	**34**
	Discomfort Index (Epstein and Moran 2006)			
Category	**No Heat Stress**	**Mild Sensation of Heat**	**Moderately Heavy Heat Load**	**Severe Heat Load**
Threshold	**< 22 units**	**□ 22 units**	**>24 units**	**> 28 units**
PD Urban	**0.2**	**1.1**	**10.1**	**80.5**
MC Urban	**0.0**	**0.1**	**2.8**	**89.0**

Human thermal comfort depends on environmental and behavioral factors – energy balance



Havenith 2003

$$M + W + Q^* + Q_H + Q_L + Q_{SW} + Q_{Re} \pm S = 0$$

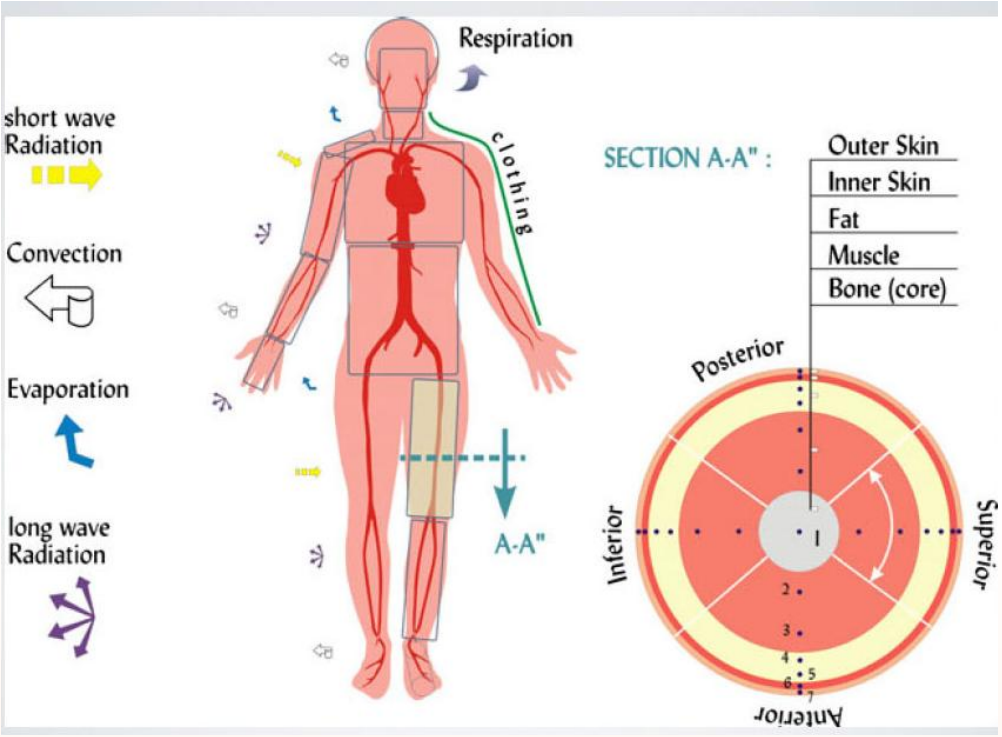
M: Metabolic Rate
W: Muscular Activity
Q^*: Radiation
Q_H : Sensible Heat
Q_L : Diffusion Water Vapor
Q_{SW} : Sweat Evaporation
Q_{Re} : Respiration
S: Body Heat Storage

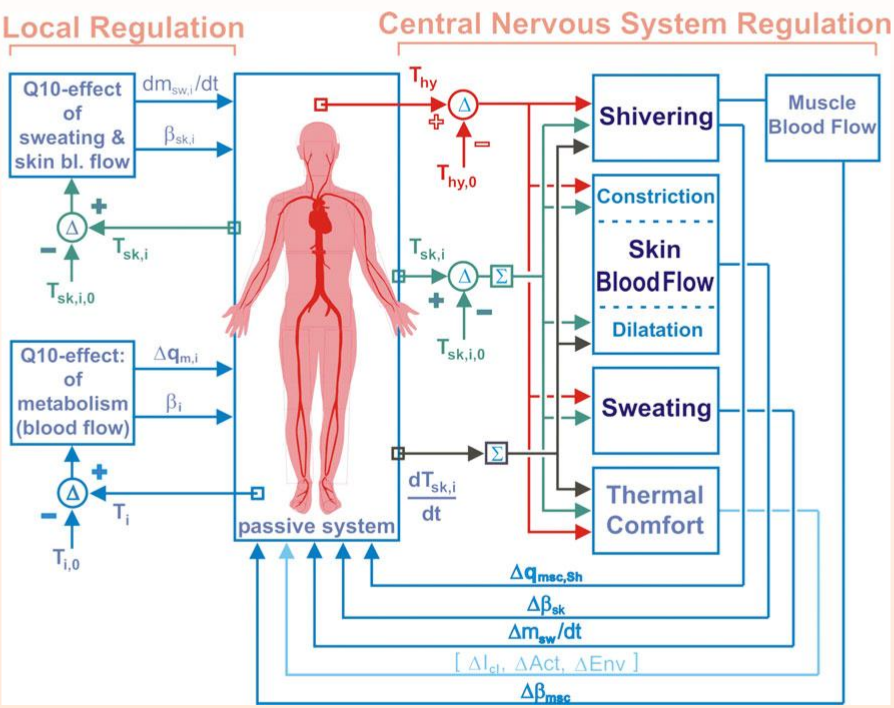
Normal Core temperature – 37.0°C

Heat Exhaustion Core temperature – 38.5°C

Heat Stroke Core temperature – 41.5°C

Prognostic Human Thermal Models

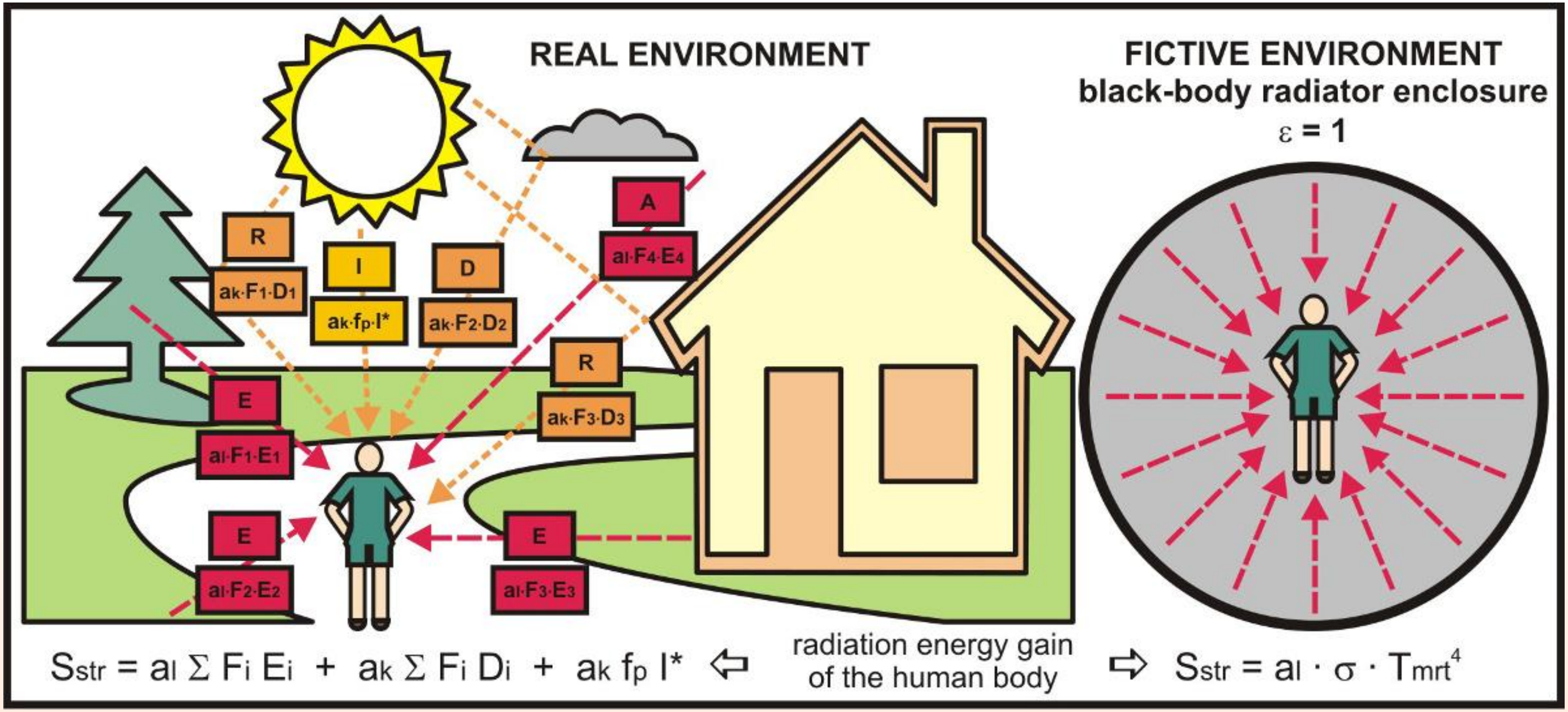




Multi-node model of human thermoregulation
(Fiala et al. 2012)

Mean Radiant Temperature

The mean radiant temperature, in relation to a given person placed in a given environment, in a given body posture and clothing, is defined as that uniform temperature of a fictive black-body radiation enclosure (emission coefficient = 1) which would result in the same net radiation energy exchange with the subject as the actual, more complex radiation environment.



Kantor and Unger 2011

Evaluation against Observations

Evaluation – Flux Tower Sites and Model Intercomparison

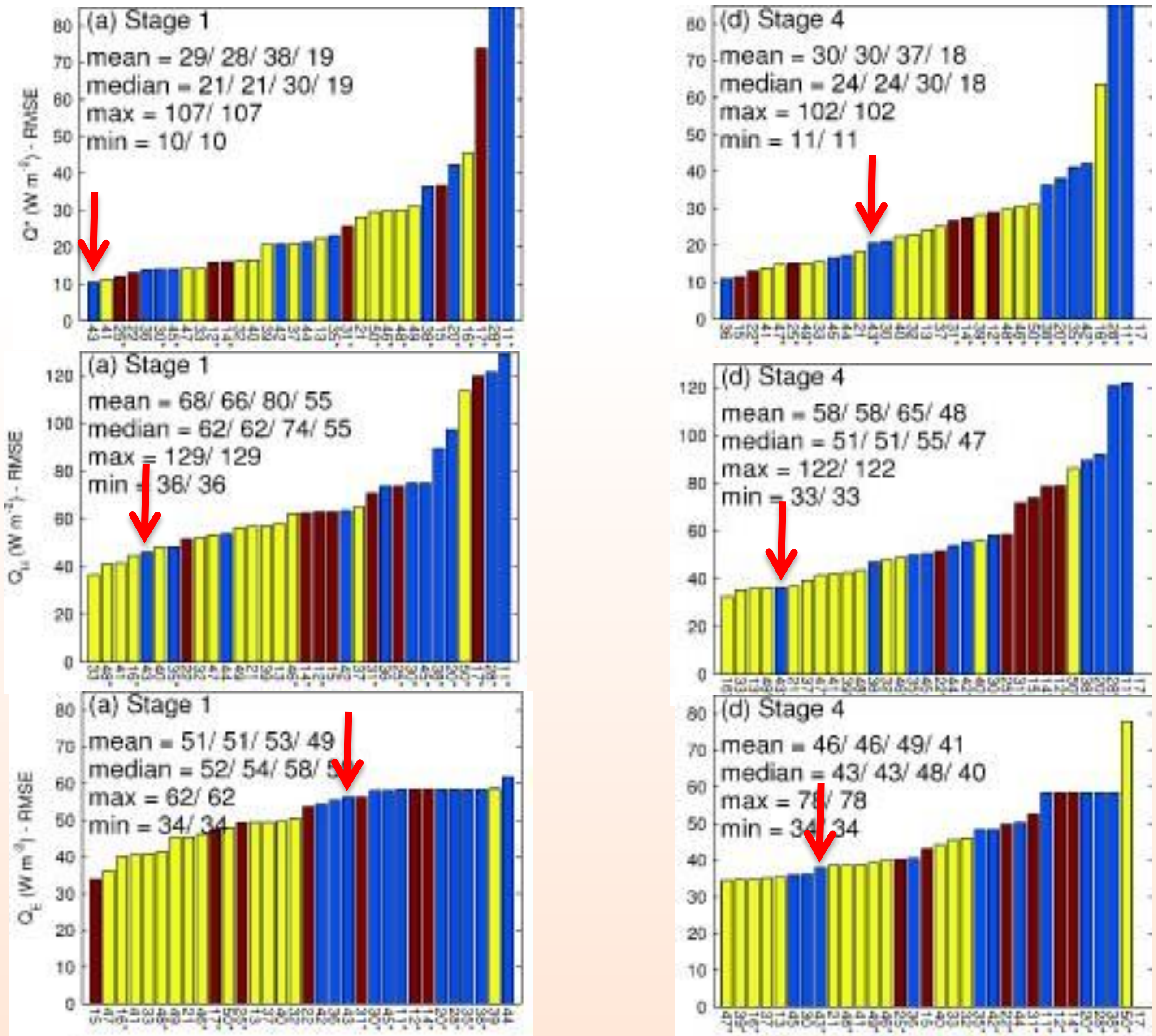
International Urban Energy Balance Model Comparison (Grimmond et al. 2010);

Aug 2003 – Nov 2004 Suburban (Preston) Melbourne, Australia

Net Radiation

Sensible Heat

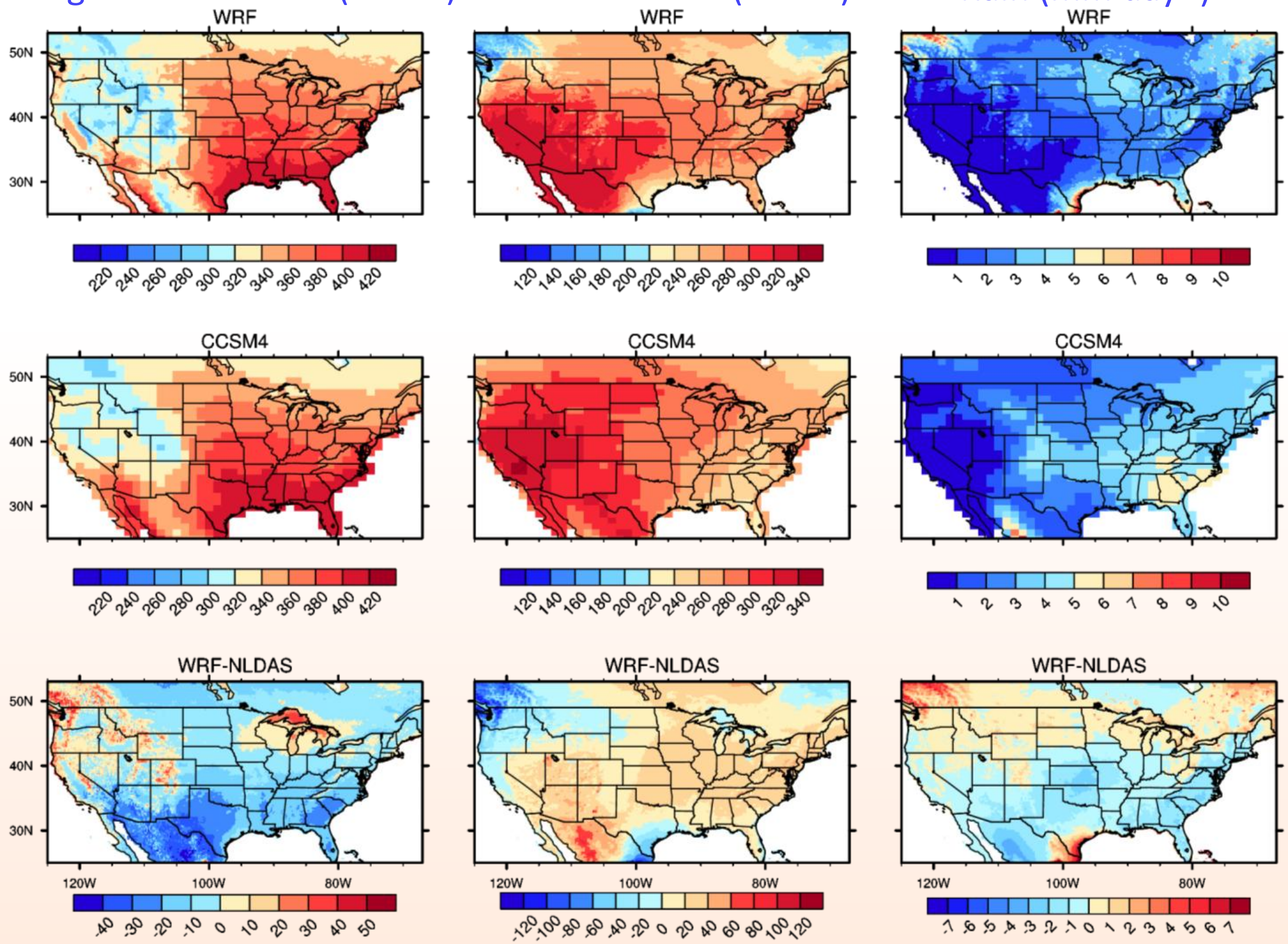
Latent Heat



WRF, CCSM4, WRF-NLDAS Atmospheric Forcing

JJA 1986-2005

Longwave Radiation (W m^{-2}) Solar Radiation (W m^{-2}) Rain (mm day^{-1})



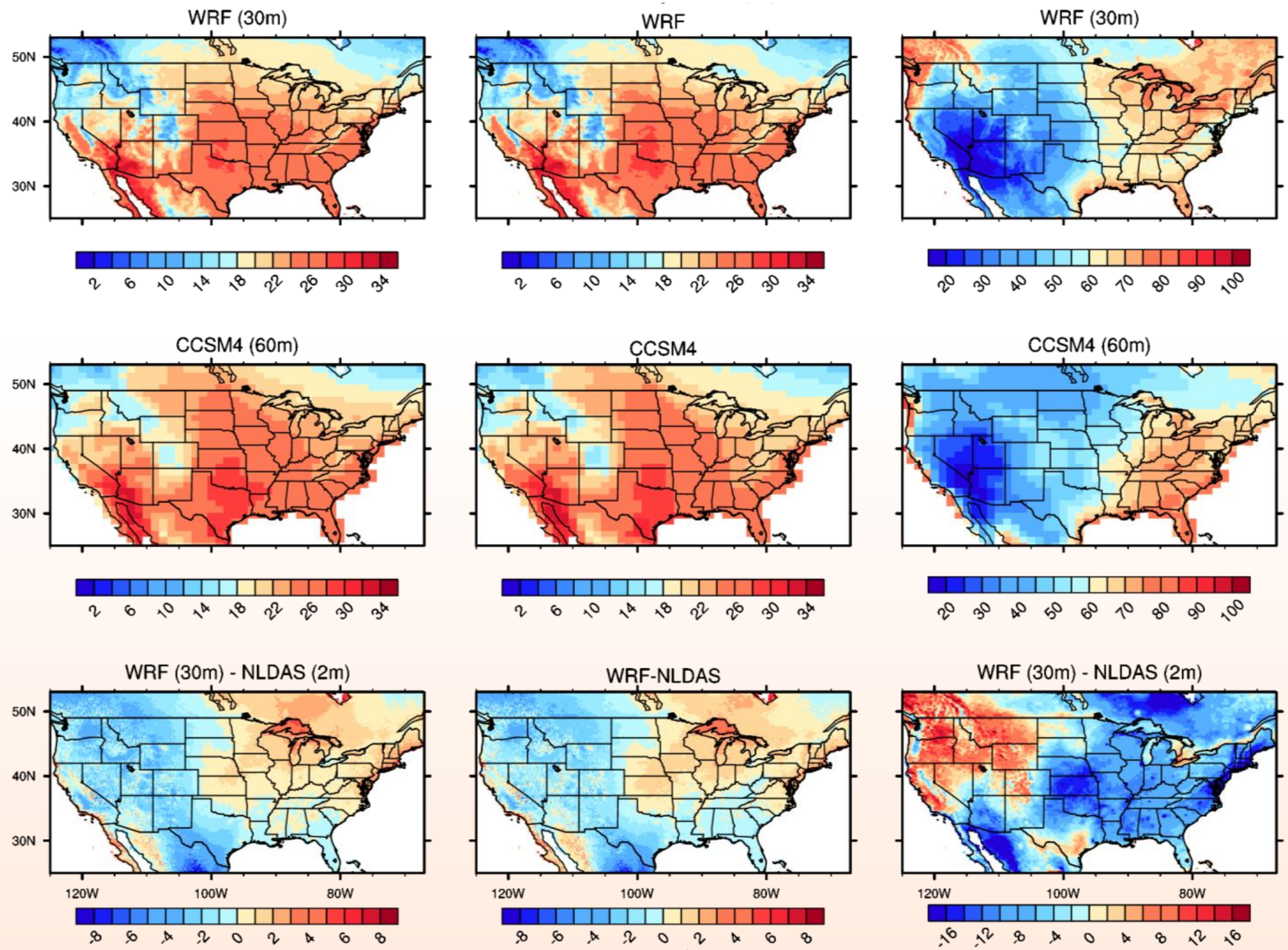
RSME = 14.6, R = 0.95 RSME = 27.6, R = 0.68 RSME = 1.3, R = 0.57

RAIN: NARCCAP-OBS (Mearns et al. 2012) Model Range: RMSE = 0.57-1.53 mm day^{-1} , R = 0.70-0.82

WRF, CCSM4, WRF-NLDAS Atmospheric Forcing

JJA 1986-2005

Atmospheric Air Temp (°C) | 2-m Air Temp (°C) | Atmospheric RH (%)

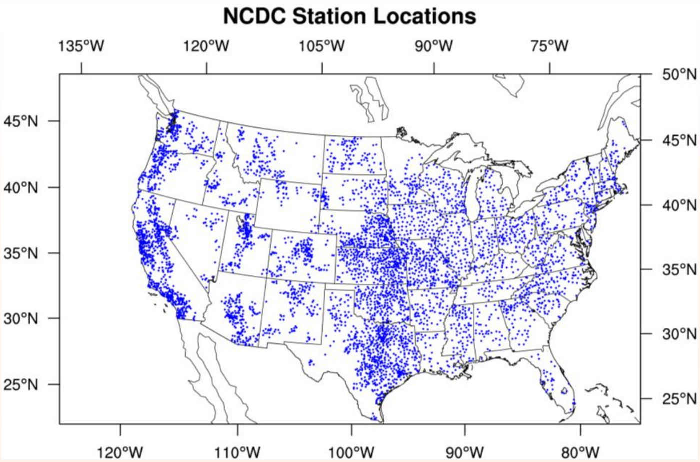


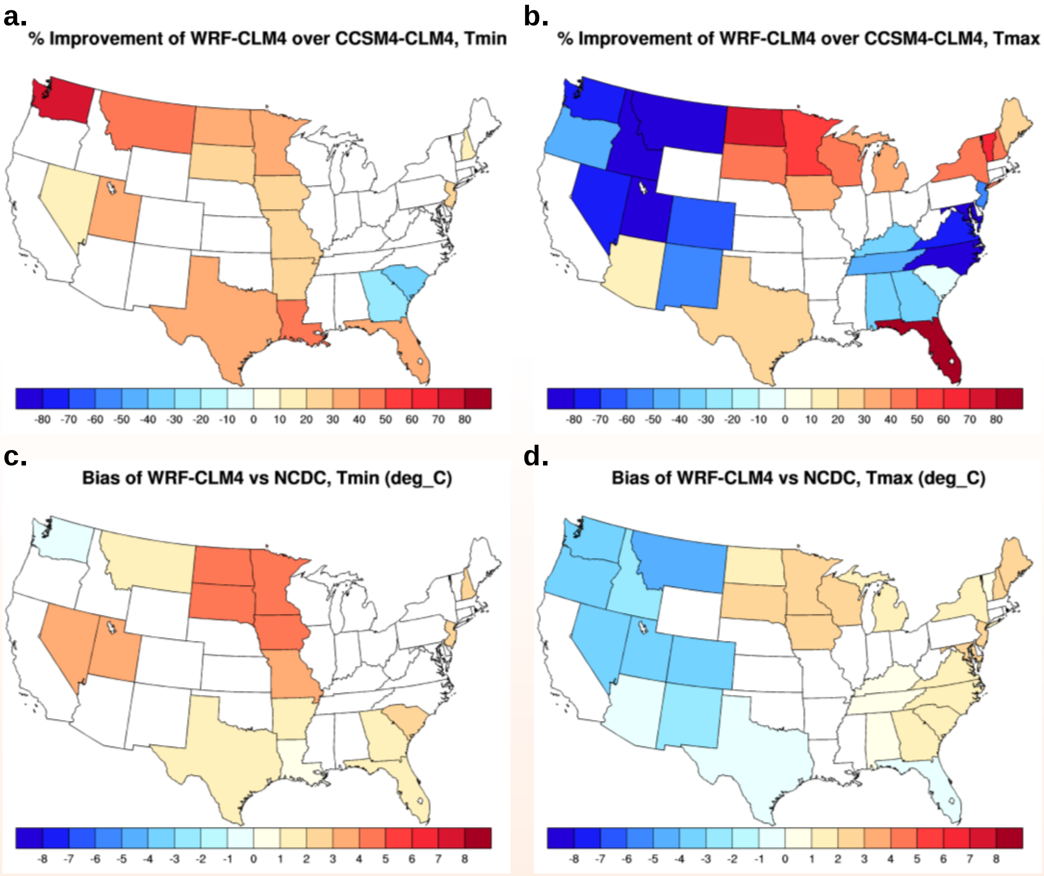
RSME = 2.0, R = 0.93 | RSME = 1.8°C, R = 0.94 | RSME = 8.6, R = 0.91

2-m Temp: NARCCAP-OBS (Mearns et al. 2012) Model Range: RMSE = 1.7-3.6 °C R = 0.93-0.97

Evaluation of Tmax and Tmin for JJA present-day

Observed daily Tmax and Tmin are obtained from 5,332 network stations of the quality controlled National Climatic Data Center (NCDC) US COOP, as documented by Meehl et al. (2009)

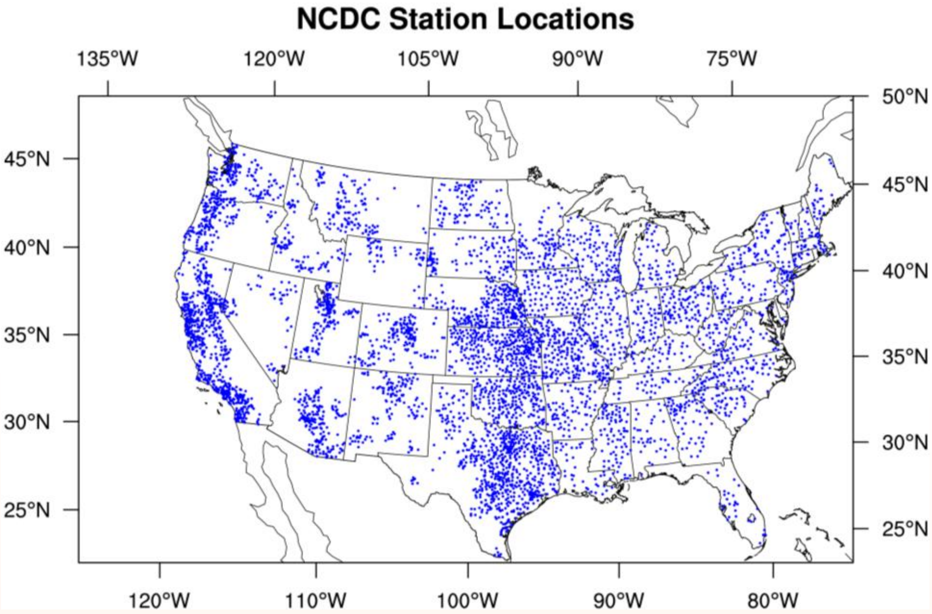




- For Tmin, WRF-CLM4 has significantly smaller biases in 15 states, larger biases in two states, and no significantly different biases in 26 states compared to CCSM4-CLM4
- For Tmax, WRF-CLM4 has significantly smaller biases in 13 states, larger biases in 17 states, and no significantly different biases in 16 states

Evaluation of heatwave intensity, duration, and frequency for present-day

Observed daily Tmax and Tmin are obtained from 5,332 network stations of the quality controlled National Climatic Data Center (NCDC) US COOP, as documented by Meehl et al. (2009)



- Model bias in heatwave intensity ranges from -0.5 to 5.3°C with a state average absolute bias of 1.3°C.
- Bias in duration ranges from -3.0 to 2.9 days/event with an average bias of 1 day/event.
- Bias in frequency ranges from -0.28 to 0.06 events/year with an average bias of 0.04 events/year.

Intensity (°C)

State	CLM	NCDC	CLM-NCDC
alabama	24.20	23.11	1.09
arkansas	24.91	23.63	1.28
arizona	25.36	22.66	2.70
california	22.64	18.50	4.14
colorado	14.98	13.25	1.73
connecticut	23.01	20.72	2.29
….	….	….	….

Duration (days/event)

State	CLM	NCDC	CLM-NCDC
alabama	5.16	6.90	-1.74
arkansas	5.95	8.22	-2.27
arizona	9.88	8.98	0.90
California	6.39	5.73	0.66
Colorado	8.58	7.23	1.35
Connecticut	6.61	5.96	0.65
….	….	….	….

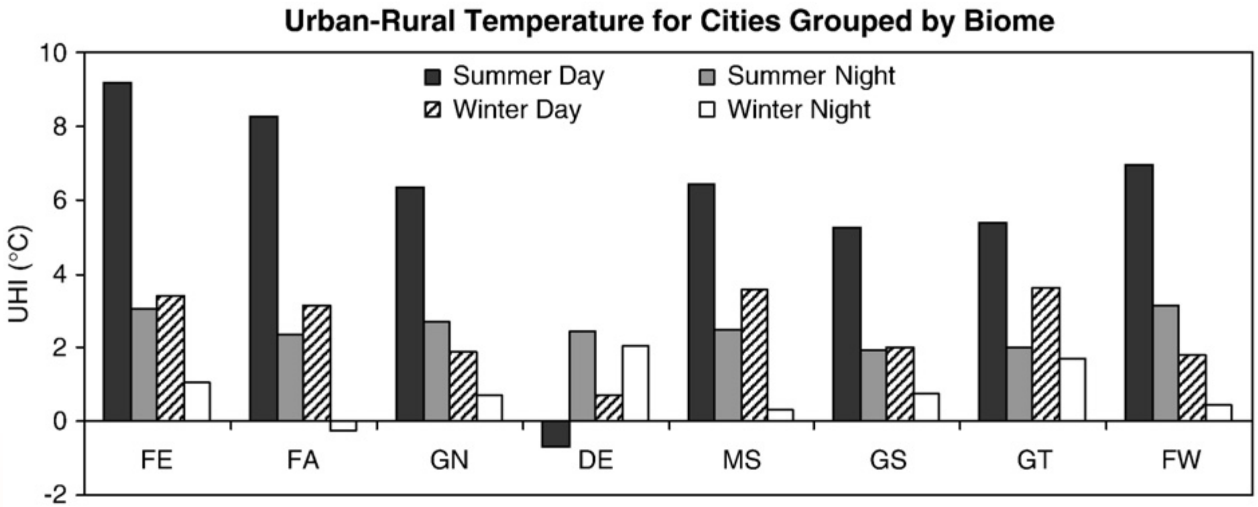
Frequency (events/year)

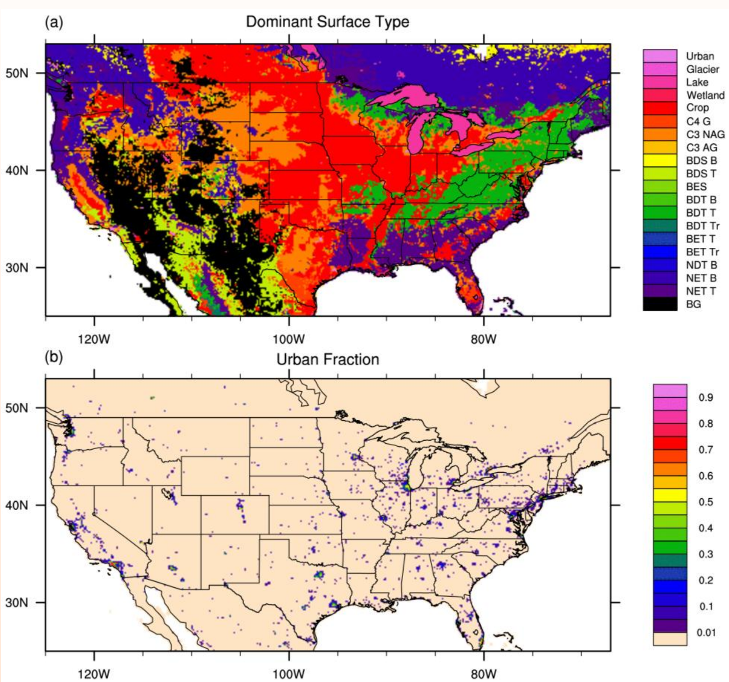
State	CLM	NCDC	CLM-NCDC
alabama	0.23	0.38	-0.15
arkansas	0.30	0.32	-0.02
arizona	0.22	0.27	-0.05
california	0.35	0.32	0.03
colorado	0.30	0.26	0.04
connecticut	0.12	0.35	-0.23
….	….	….	….

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, savannahs, and shrublands
DE – Desert and xeric shrublands
MS – Mediterranean forests, woodlands, shrub (California)
GS – Temperate grasslands, savannahs, and shrublands (Texas)
GT – Tropical and subtropical grasslands, savannahs, and shrublands (Houston, New Orleans
FW – Temperate coniferous forest (Oregon, Washington)

Imhoff et al. 2010, RSE, Fig. 4



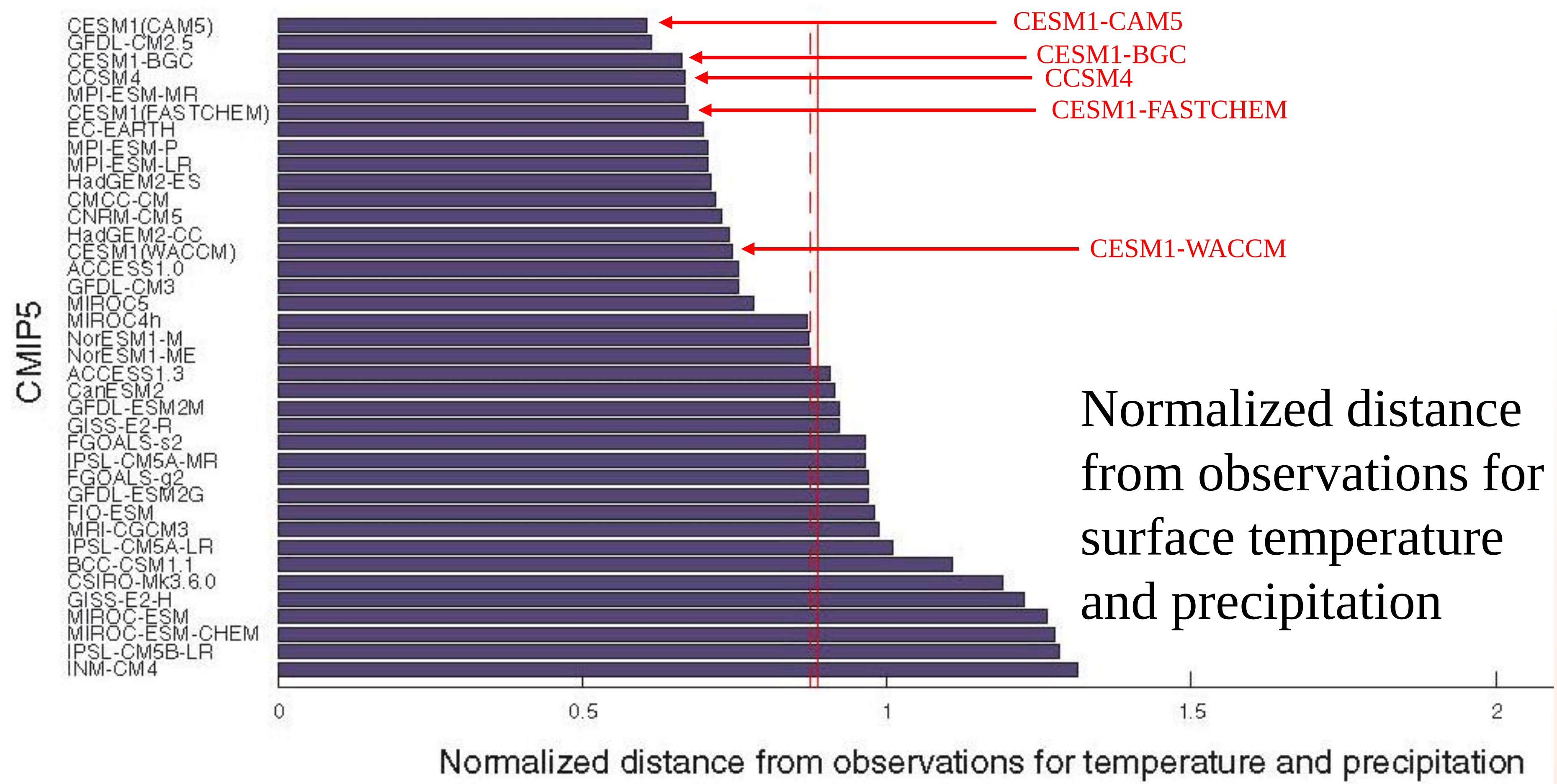


CLMU Daily Average Surface UHI (°C)

	Summer	*Winter*
NET	*5.7*	*2.1*
BDT	*5.3*	*2.6*
Crop	*4.7*	*2.8*
C3/C4 Grass	*4.7/4.8*	*2.8/1.6*
Bare Ground	*4.3*	*3.2*
BDS	*3.6*	*2.2*

CESM

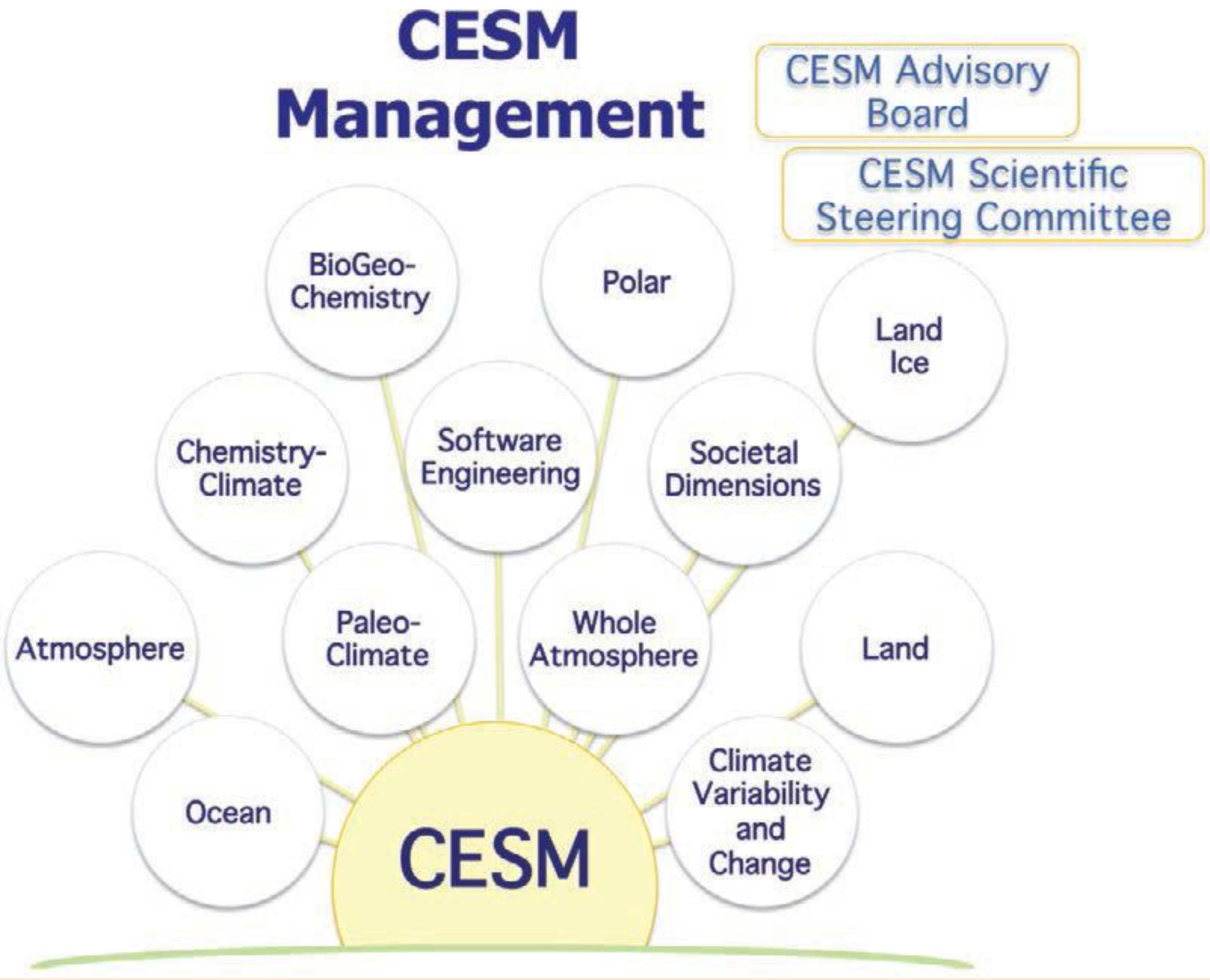
CMIP5 Model Intercomparison – IPCC AR5



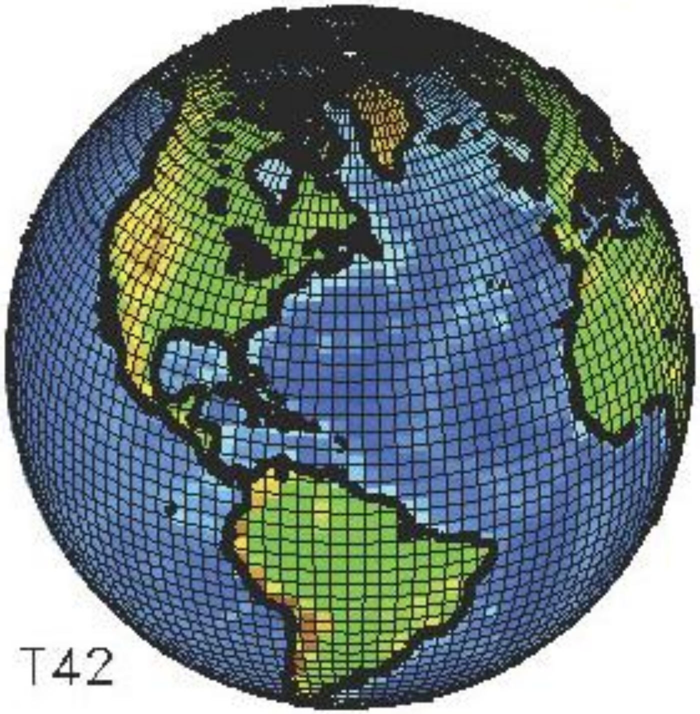
Knutti, Masson, Gettelman, GRL, 2013

"…strong caveat … linking model performance metrics to model quality or skill is difficult, subjective, and strongly metric dependent."

CESM Governance Structure

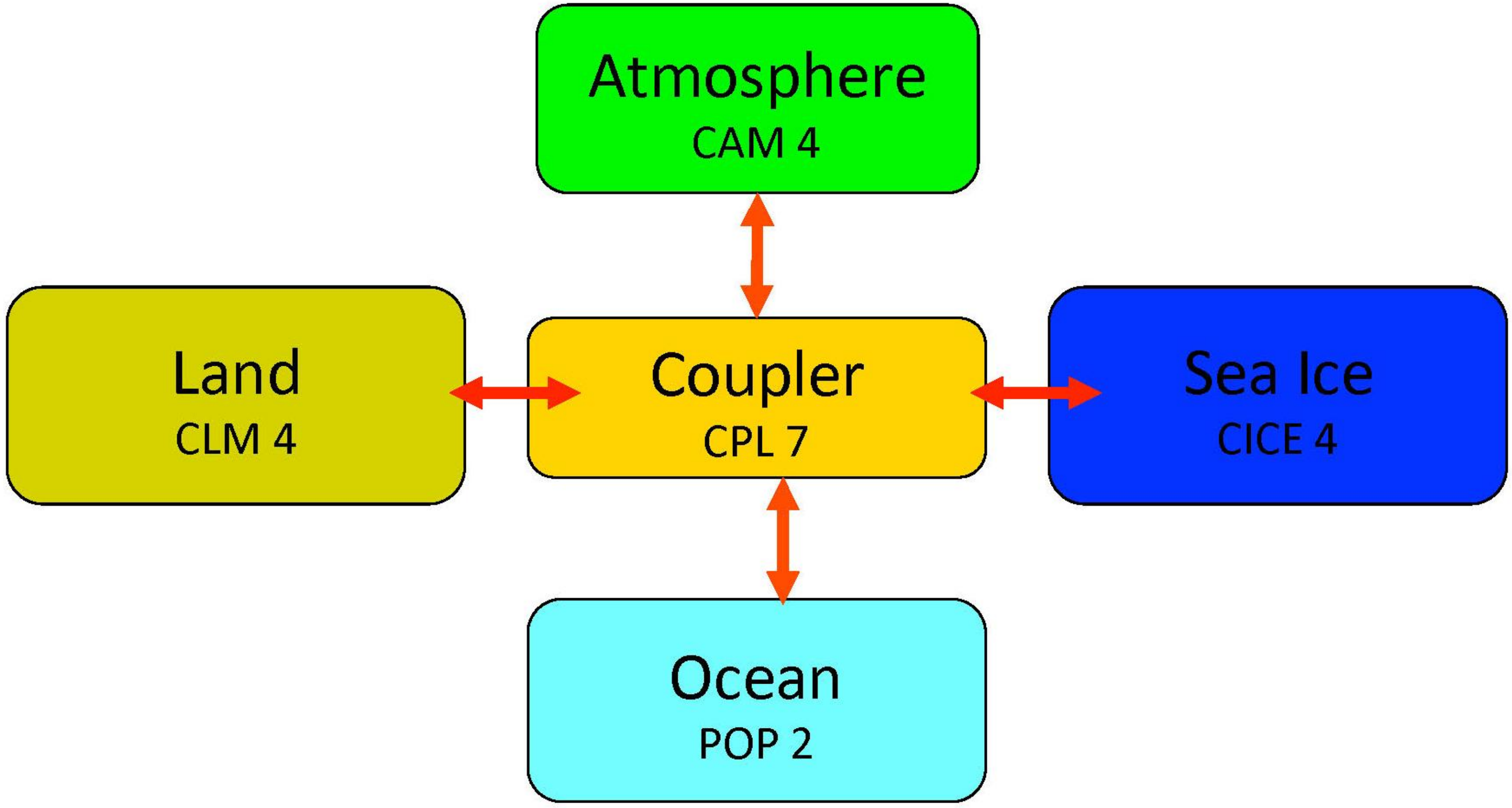


Community Earth System Model (CESM1)



Core is a Coupled Ocean-Atmosphere-Land - Sea Ice model (CCSM4)

- 0.25°, 0.5°, 1° , 2°, T31 resolutions
- 30 minute time step
- 26 atmosphere levels
- 60 ocean levels
- 15 ground layers
- ~5 million grid boxes at 1°
- ~1.5 million lines of computer code
- Archive data (monthly, daily, hourly) for hundreds of geophysical fields (over 250 in land model alone)


Atmosphere
CAM 4
Land
CLM 4
Coupler
CPL 7
Sea Ice
CICE 4
Ocean
POP 2

UHI

Processes contributing to the Urban Heat Island

- 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, human metabolism)

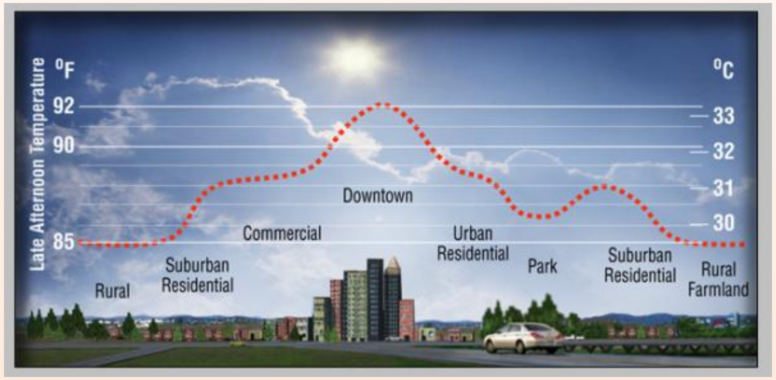
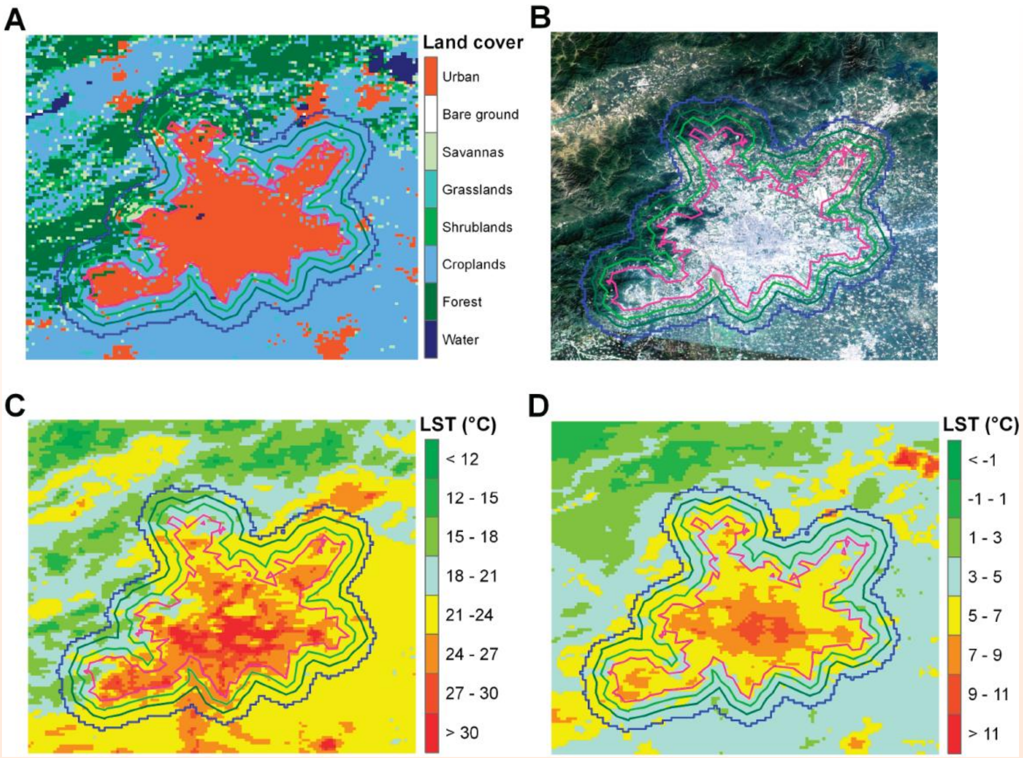


Image courtesy of Heat Island Group, Lawrence Berkeley National Laboratory

For more information see papers by Tim Oke and colleagues

The Urban Heat Island (UHI)

- The UHI is defined as the relative warmth of a city compared to the surrounding “rural” 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).

Source: Peng et al, 2012, EST