Urban Street-Scale Climate Simulations for Sustainability, Health, and Social Equity

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Abstract

Intra-urban fine-scale data and models are needed to understand infrastructure interactions that shape equity and health related to extreme heat, cold and precipitation events. Fine-scale data are needed to address spatial equity at the scale of city blocks or block groups where income and race data are available. We conducted nested simulations with the Weather Research and Forecasting (WRF) model that cover parts of the US state of Minnesota — one of the fastest warming states in the contiguous US. The first two nests at 5km and 1km horizontal resolution cover the counties of southern Minnesota, with the outer 5km grid also covering some counties in the neighboring states Iowa and Wisconsin. Within the 1km inner grid, we created two additional nests. The third grid covers the metropolitan region of the Twin Cities Minneapolis and Saint Paul at 200m resolution. Within this grid, we created a fourth nest over a 4x4km neighborhood in downtown Minneapolis that includes the campus of the University of Minnesota at 40m resolution. All model nests have 82 vertical levels. Lateral input data were acquired from the global Coupled Forecast System (CFS) analysis at 30km horizontal resolution. The boundary conditions consist of high-resolution land use data including vegetation types, urban fraction, building heights and shapes. The input data were specifically designed by the Remote Sensing and Geospatial Analysis Laboratory at the University of Minnesota and cover the whole Twin Cities Metro Area (TCMA) at 1m horizontal resolution. This dataset was derived from a multi-temporal composite of aerial imagery from the summer of 2015 and fall of 2009-2011, and lidar data of 2011 and 2012. The vertical accuracy of the lidar data meets or exceeds 12.5cm root mean square error (RMSE). The results of our model simulations show remarkable fine-scale climate responses to changes in vegetation cover and albedo that are going to be used for various urban planning projects.

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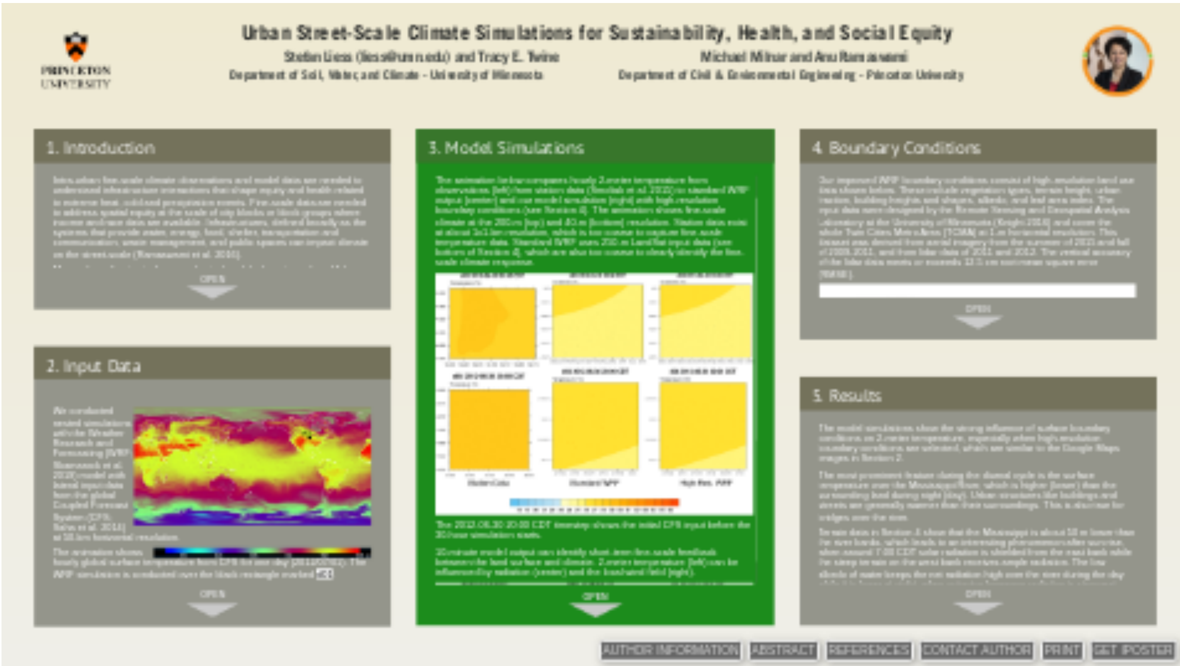

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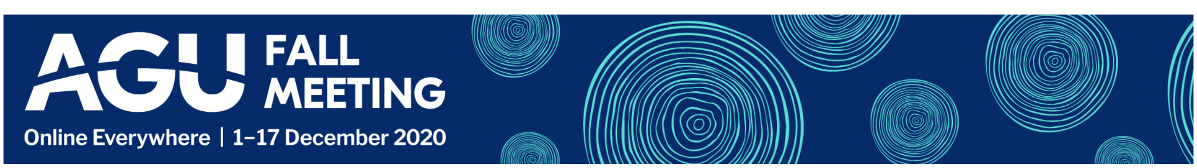
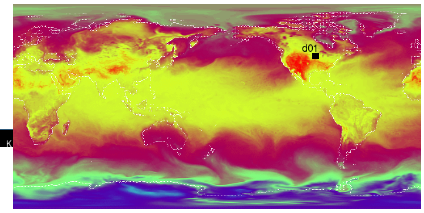


1. INTRODUCTION

Intra-urban fine-scale climate observations and model data are needed to understand infrastructure interactions that shape equity and health related to extreme heat, cold and precipitation events. Fine-scale data are needed to address spatial equity at the scale of city blocks or block groups where income and race data are available. Infrastructures, defined broadly as the systems that provide water, energy, food, shelter, transportation and communication, waste management, and public spaces can impact climate on the street-scale (Ramaswami et al. 2016).

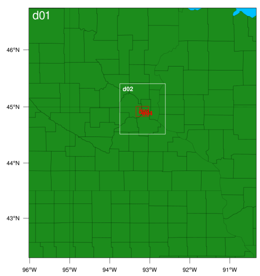
Many urban climate studies use physical models down to scales of 1 km (Barlage et al. 2016) or even 200 m (Kon, 2020), or use less reliable statistical models (Wicki et al. 2018). We configured a physical model for the 40-m scale, which is below the size of a typical block and can address the impact of individual large buildings and spaces on the fine-scale climate, also called urban microclimate (Morgan et al. 1977), which influences human well-being and sustainability.

2. INPUT DATA

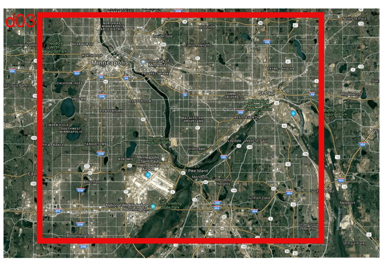


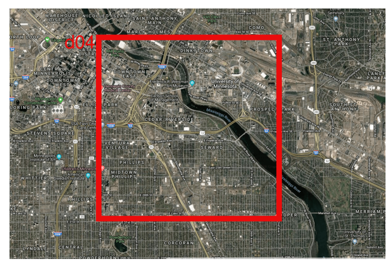
We conducted nested simulations with the Weather Research and Forecasting (WRF; Skamarock et al. 2019) model with lateral input data from the global Coupled Forecast System (CFS; Saha et al. 2014) at 50-km horizontal resolution.

The animation shows hourly global surface temperature from CFS for one day (2012/07/01). The WRF simulation is conducted over the black rectangle marked d01.



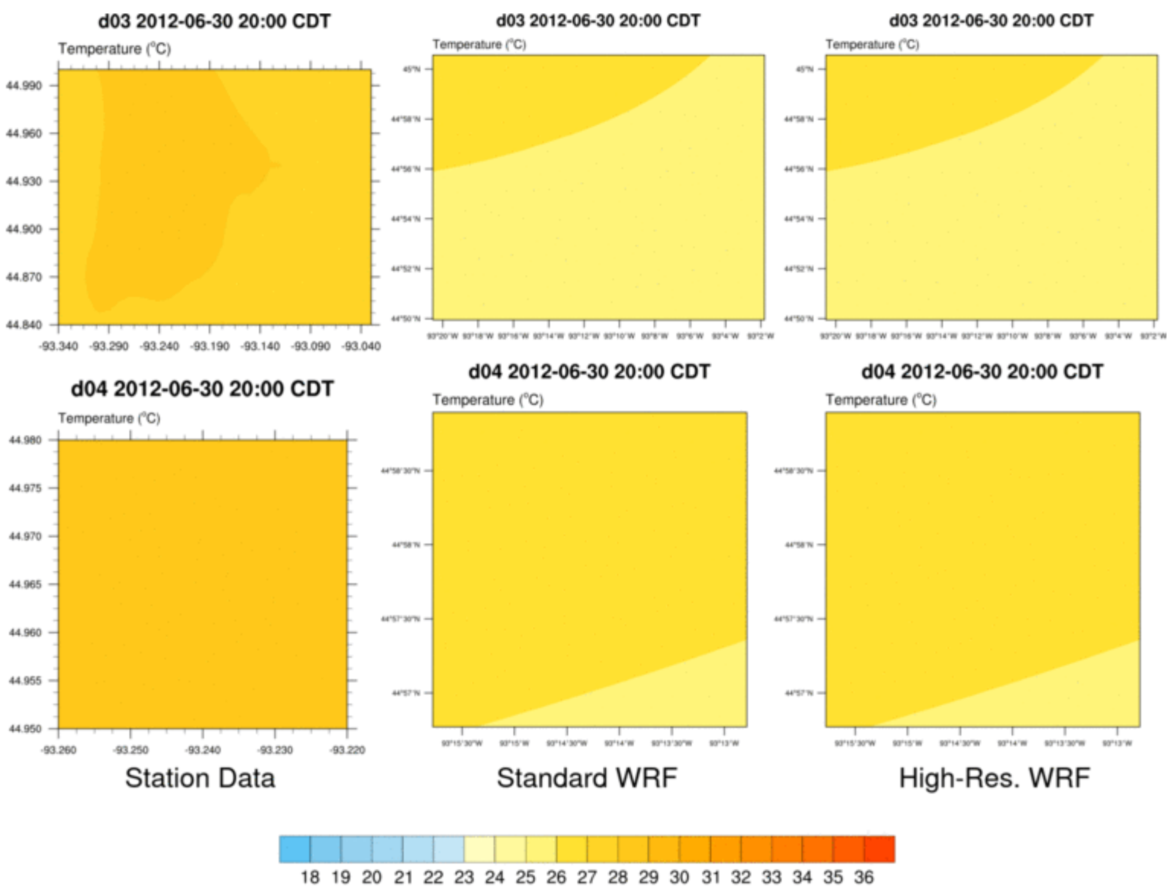
This region covers parts of the US state of Minnesota — one of the fastest warming states in the contiguous US. The left figure shows the first two nests at 5-km (d01) and 1-km (d02) horizontal resolution over the counties of southern Minnesota, with the outer 5-km grid also covering some counties in the neighboring states of Iowa and Wisconsin. Within the 1-km inner grid, we created two additional nests. The third grid covers large parts of the Minneapolis and Saint Paul Twin Cities Metro Area (TCMA) at 200-m resolution (d03). Within the northwestern quadrant of this grid, we created a fourth nest over a 4x4-km neighborhood in downtown Minneapolis that includes the campus of the University of Minnesota at 40-m resolution (d04). These two nests are marked in red in the Google Maps images below. All four model nests have 80 vertical levels within the troposphere and lower stratosphere.





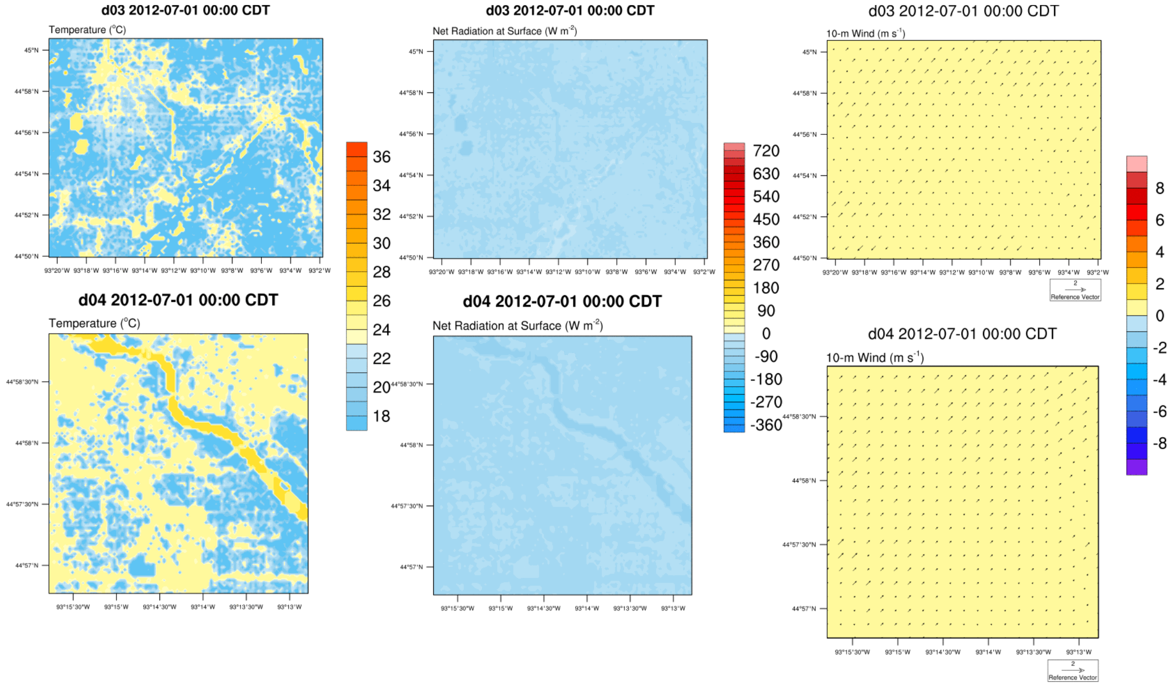
3. MODEL SIMULATIONS

The animation below compares hourly 2-meter temperature from observations (left) from station data (Smoliak et al. 2015) to standard WRF output (center) and our model simulation (right) with high-resolution boundary conditions (see Section 4). The animation shows fine-scale climate at the 200-m (top) and 40-m (bottom) resolution. Station data exist at about 1x1-km resolution, which is too coarse to capture fine-scale temperature data. Standard WRF uses 250-m LandSat input data (see bottom of Section 4), which are also too coarse to clearly identify the fine-scale climate response.



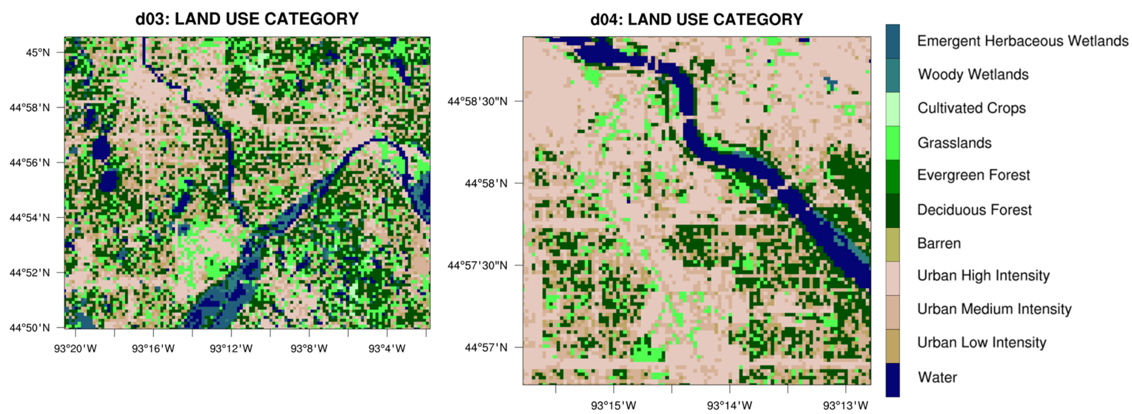
The 2012-06-30 20:00 CDT timestep shows the initial CFS input before the 30-hour simulation starts.

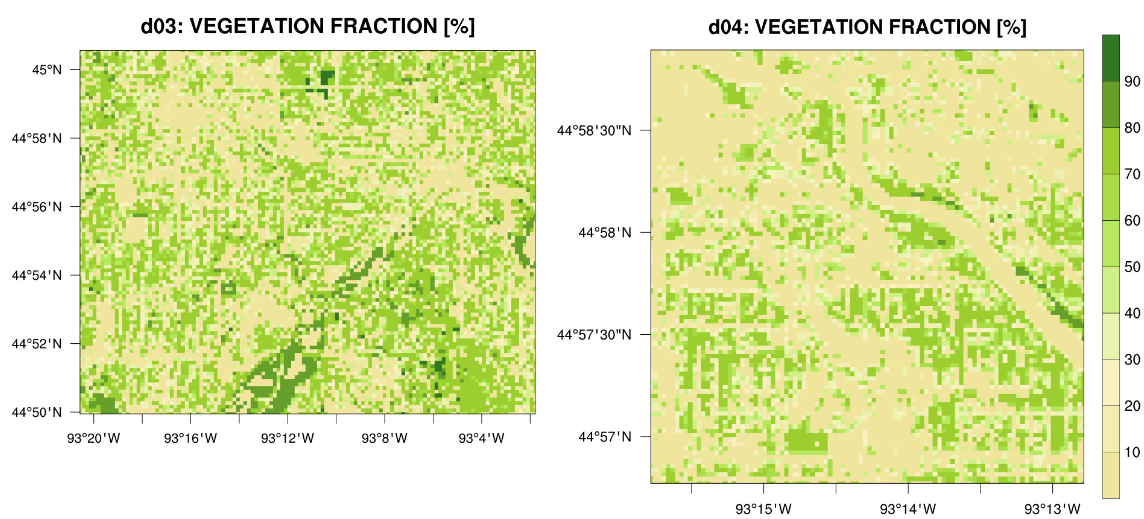
10-minute model output can identify short-term fine-scale feedback between the land surface and climate. 2-meter temperature (left) can be influenced by radiation (center) and the local wind field (right).

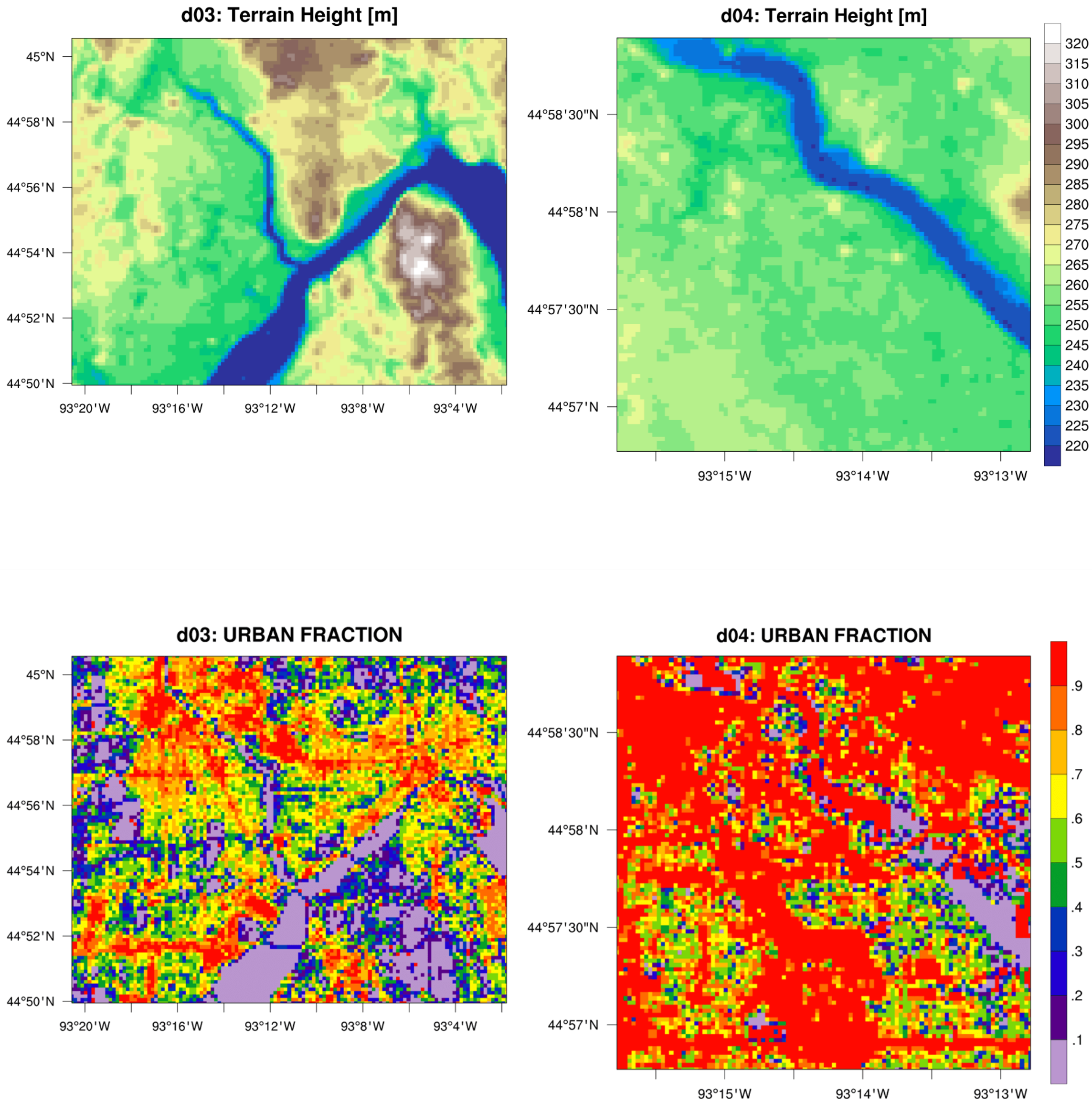

d03 2012-07-01 00:00 CDT
Temperature (°C)
d03 2012-07-01 00:00 CDT
Net Radiation at Surface (W m-2)
d03 2012-07-01 00:00 CDT
10-m Wind (m s-1)
d04 2012-07-01 00:00 CDT
Temperature (°C)
d04 2012-07-01 00:00 CDT
Net Radiation at Surface (W m-2)
d04 2012-07-01 00:00 CDT
10-m Wind (m s-1)
36
34
32
30
28
26
24
22
20
18
720
630
540
450
360
270
180
90
0
-90
-180
-270
-360
8
6
4
2
0
-2
-4
-6
-8
Reference Vector
Reference Vector

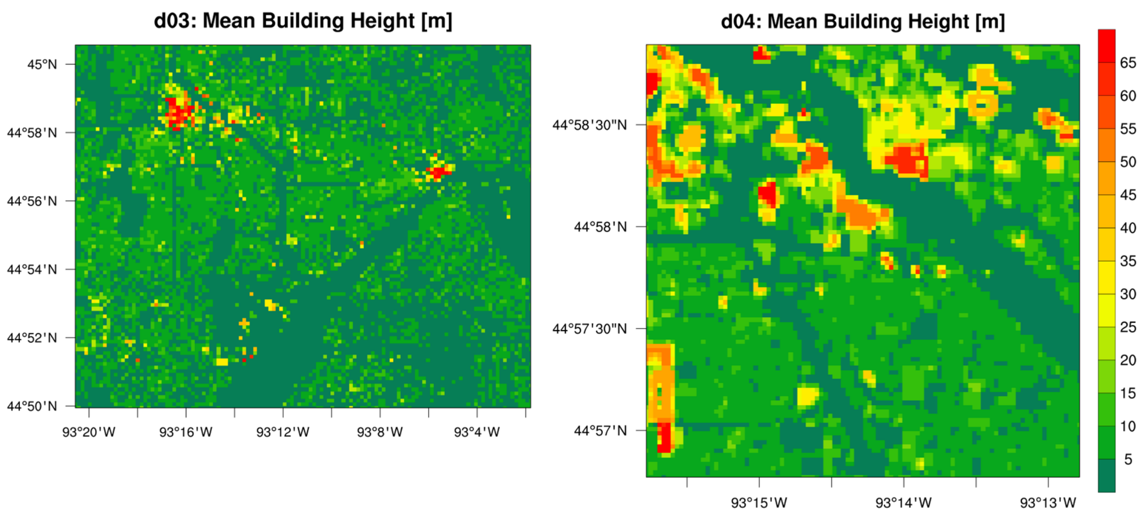
4. BOUNDARY CONDITIONS

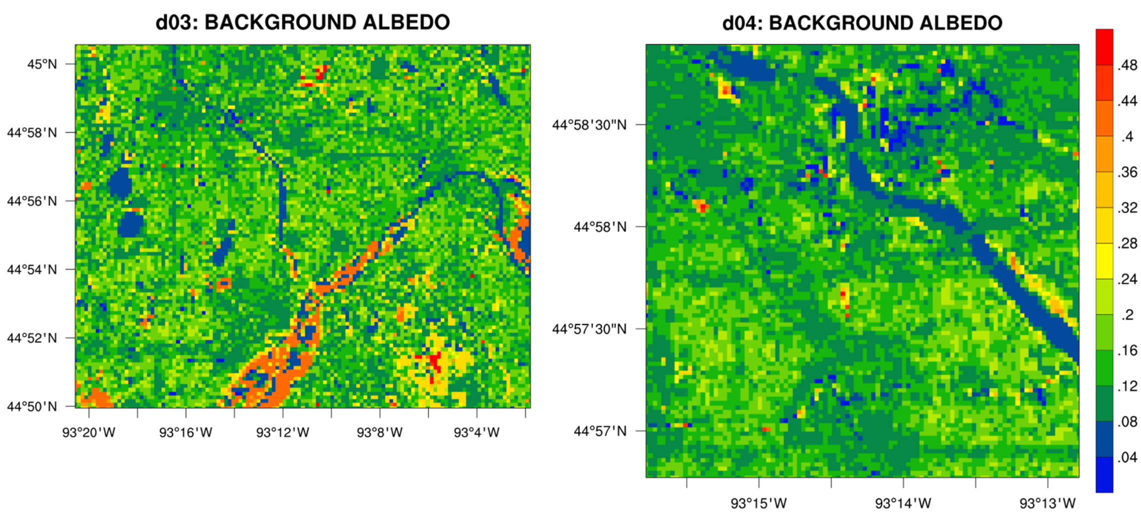
Our improved WRF boundary conditions consist of high-resolution land use data shown below. These include vegetation types, terrain height, urban fraction, building heights and shapes, albedo, and leaf area index. The input data were designed by the Remote Sensing and Geospatial Analysis Laboratory at the University of Minnesota (Knight 2016) and cover the whole Twin Cities Metro Area (TCMA) at 1-m horizontal resolution. This dataset was derived from aerial imagery from the summer of 2015 and fall of 2009-2011, and from lidar data of 2011 and 2012. The vertical accuracy of the lidar data meets or exceeds 12.5 cm root mean square error (RMSE).

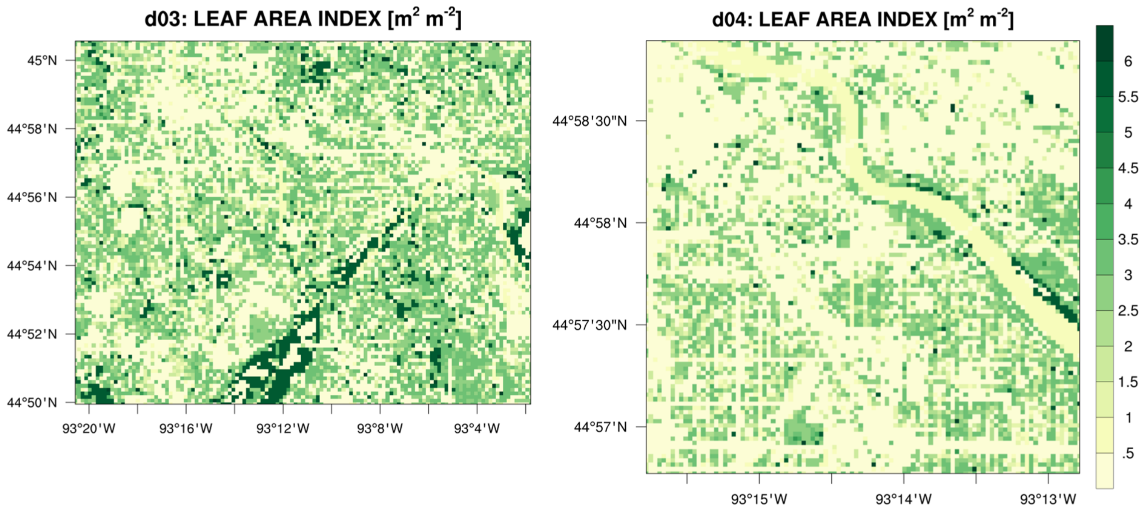




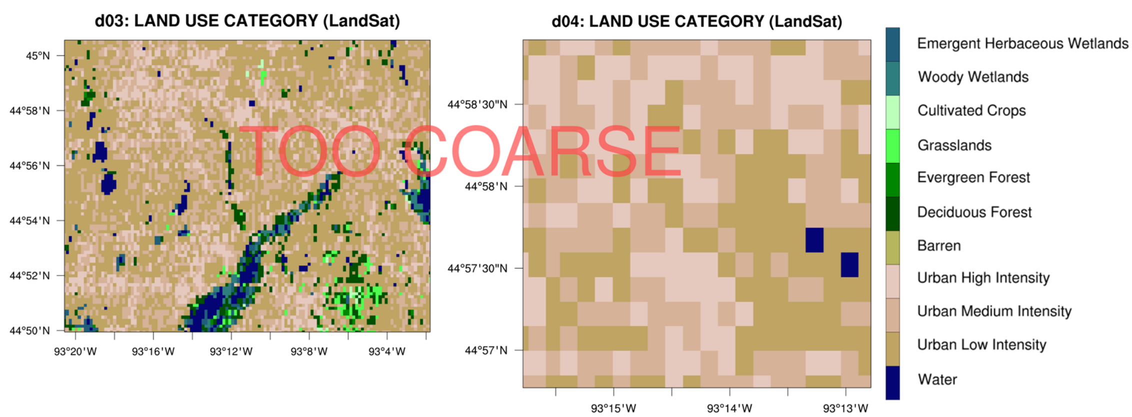

d03: Terrain Height [m]
d04: Terrain Height [m]
45°N
44°58'N
44°56'N
44°54'N
44°52'N
44°50'N
93°20'W
93°16'W
93°12'W
93°8'W
93°4'W
44°58'30"N
44°58'N
44°57'30"N
44°57'N
93°15'W
93°14'W
93°13'W
320
315
310
305
300
295
290
285
280
275
270
265
260
255
250
245
240
235
230
225
220
d03: URBAN FRACTION
d04: URBAN FRACTION
.9
.8
.7
.6
.5
.4
.3
.2
.1


d03: Mean Building Height [m]
45°N
44°58'N
44°56'N
44°54'N
44°52'N
44°50'N
93°20'W
93°16'W
93°12'W
93°8'W
93°4'W
d04: Mean Building Height [m]
44°58'30"N
44°58'N
44°57'30"N
44°57'N
93°15'W
93°14'W
93°13'W
65
60
55
50
45
40
35
30
25
20
15
10
5


d03: BACKGROUND ALBEDO
45°N
44°58'N
44°56'N
44°54'N
44°52'N
44°50'N
93°20'W
93°16'W
93°12'W
93°8'W
93°4'W
d04: BACKGROUND ALBEDO
44°58'30"N
44°58'N
44°57'30"N
44°57'N
93°15'W
93°14'W
93°13'W
.48
.44
.4
.36
.32
.28
.24
.2
.16
.12
.08
.04



Standard WRF uses LandSat data at 250-m resolution (shown below). These are insufficient for our high-resolution urban climate modeling.



5. RESULTS

The model simulations show the strong influence of surface boundary conditions on 2-meter temperature, especially when high-resolution boundary conditions are selected, which are similar to the Google Maps images in Section 2.

The most prominent feature during the diurnal cycle is the surface temperature over the Mississippi River, which is higher (lower) than the surrounding land during night (day). Urban structures like buildings and streets are generally warmer than their surroundings. This is also true for bridges over the river.

Terrain data in Section 4 show that the Mississippi is about 50 m lower than the river banks, which leads to an interesting phenomenon after sun rise, when around 7:00 CDT solar radiation is shielded from the east bank while the steep terrain on the west bank receives ample radiation. The low albedo of water keeps the net radiation high over the river during the day while it is lower at night, when outgoing longwave radiation is strongest over the river because of the high heat capacity of water. Fine-scale changes in surface winds can lead to short-term temperature changes, as seen around 2:00 CDT, when atmospheric waves from the northwest propagate through the finer d04 grid.

These regional responses to land use categories like vegetation cover and albedo are going to be used for various urban planning projects not only for current climate but also for future climate change scenarios.

AUTHOR INFORMATION

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