Creating a Virtual Utility District: Assessing Quality and Building Energy Impacts of Microclimate Simulations

Presented at:

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Cambridge, UK

Presented by:

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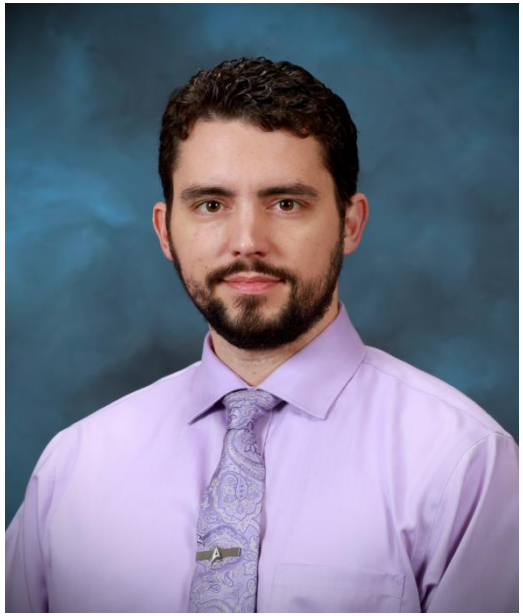
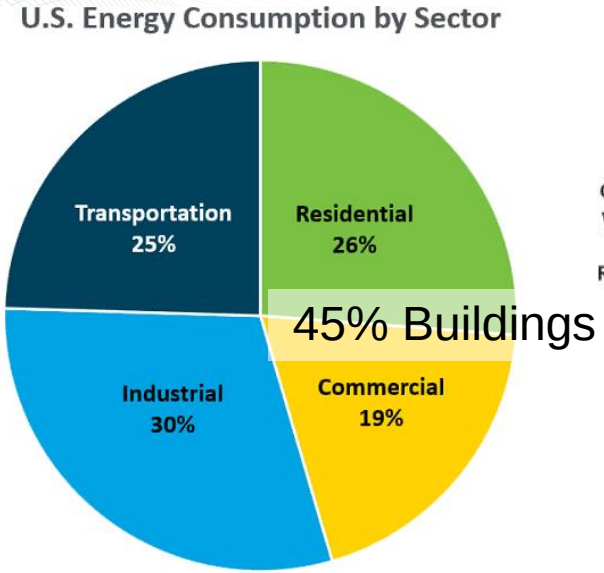
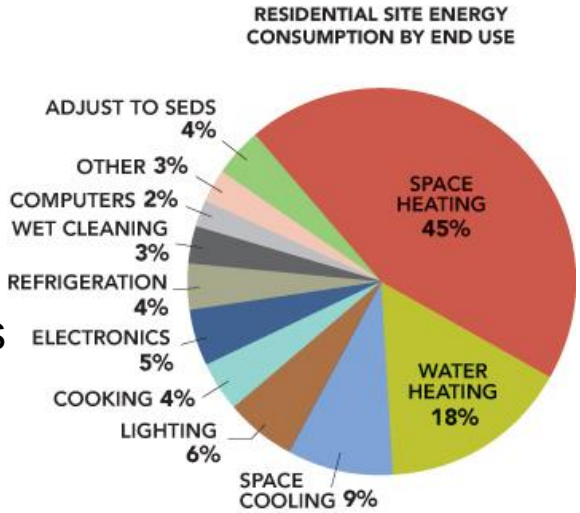
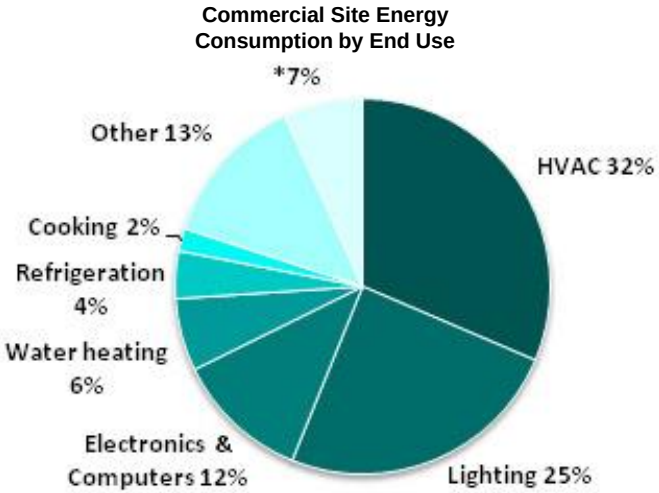


- **Career**
  - 2009+ Oak Ridge National Laboratory, R&D staff
    - ETSD, Building Technology Research & Integration Center (BTRIC), Building Envelope & Urban Systems Research Group (BEUSR)
  - 2012+ The University of Tennessee, Joint Faculty
- **Education**
  - The University of TN, (2004-2009), Knoxville; Ph.D. Comp. Sci.
  - Jacksonville State University, AL (1997-2001, 2001-2004) M.S. Systems&Software Design, double-B.S. Computer Science and Mathematics, Physics minor
- **Professional Involvement**
  - AEE, Lifetime Member, Certified Energy Manager, Certified Measurement & Verification Professional
  - PMI, Member, Project Management Professional
  - IEEE, Senior Member
  - ASHRAE, defines international building codes
    - TC1.5, Computer Applications, Voting member and officer
    - TC4.7, Energy Calculations, Voting member and officer
    - TC4.2, Climatic Information, Voting member and officer
    - SSPC169, Weather Data for Building Design Standards (24% of page count of building code), Voting member
    - SSPC140 and ASHRAE Guideline 14 involvement

Energy Consumption and Production







Buildings consume 73% of the nation's electricity

Source: U.S. Energy Information Administration, January 2016 to January 2017, *Monthly Energy Review* – Table 2.1.

124 million U.S. buildings
$395 billion/yr energy bills

Goal of the DOE
Building Technologies Office:
45% energy reduction per sq. ft.
by 2030 compared to 2010 baseline

Building Energy Modeling – building descriptions + weather = estimated building energy consumption

$9B/yr – ESCO; $7B/yr – utility EE
$14B/yr – DR management systems
0.3% modified, BEM < 10% of those

Climate and U.S. Buildings

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ASHRAE Climate Zones

- Based on weather stations, most w/ 18+ yrs of quality data (1961-1990)

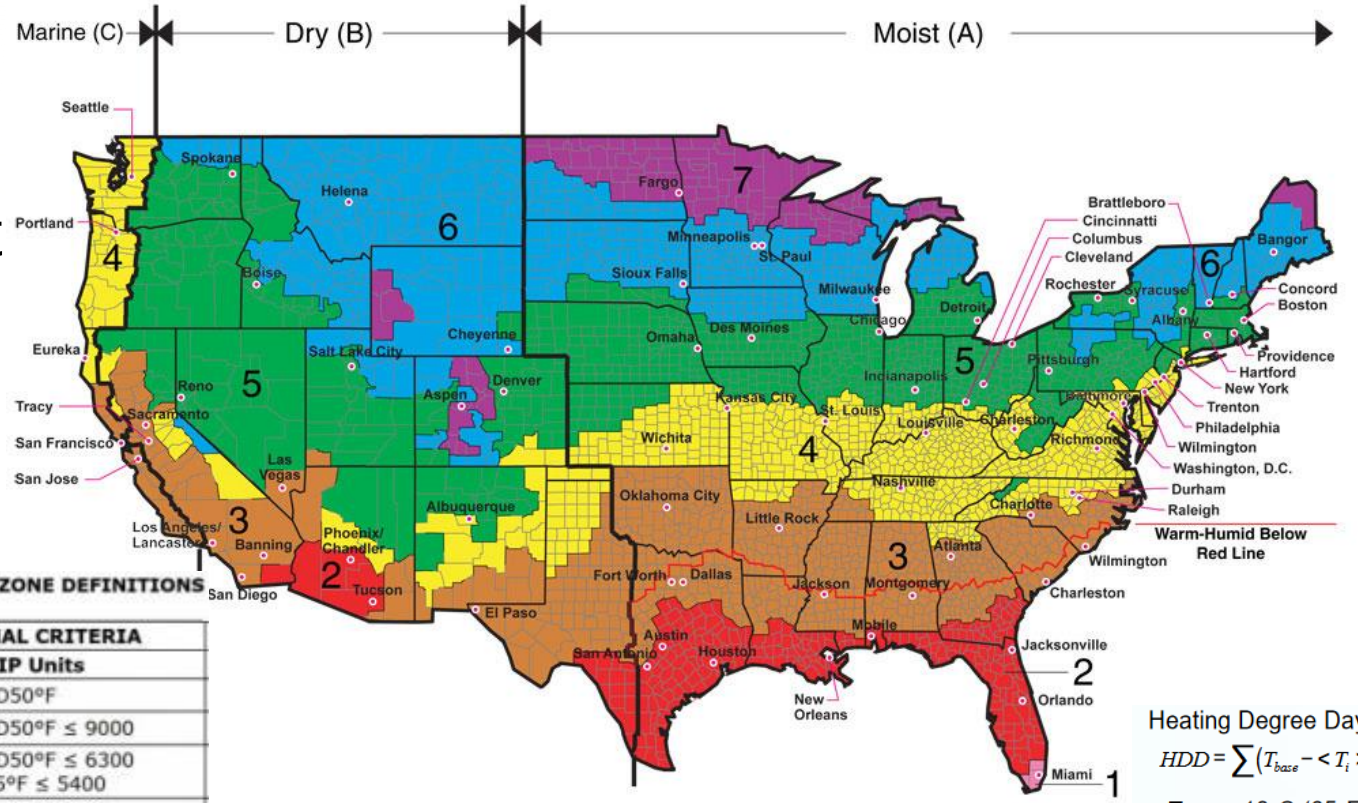


TABLE 301.3(2) INTERNATIONAL CLIMATE ZONE DEFINITIONS

ZONE NUMBER	THERMAL CRITERIA IP Units
1	9000 < CDD50°F
2	6300 < CDD50°F ≤ 9000
3A and 3B	4500 < CDD50°F ≤ 6300 AND HDD65°F ≤ 5400
4A and 4B	CDD50°F ≤ 4500 AND HDD65°F ≤ 5400
3C	HDD65°F ≤ 3600
4C	3600 < HDD65°F ≤ 5400
5	5400 < HDD65°F ≤ 7200
6	7200 < HDD65°F ≤ 9000
7	9000 < HDD65°F ≤ 12600
8	12600 < HDD65°F

Heating Degree Days:

$$HDD = \sum (T_{base} - \langle T_i \rangle)^+$$

T_{base} = 18°C (65°F)

Cooling Degree Days:

$$CDD = \sum (\langle T_i \rangle - T_{base})^+$$

T_{base} = 10°C (50°F)

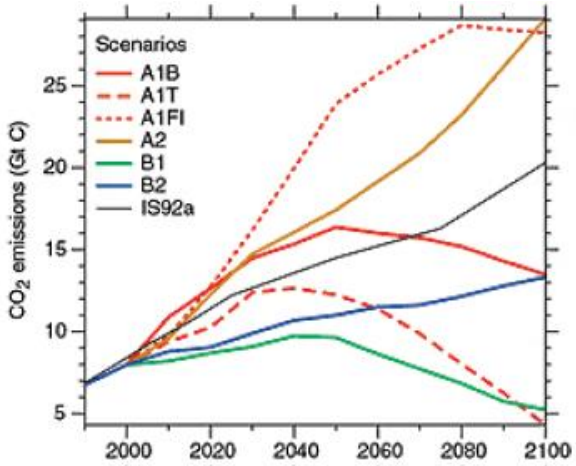
Updated every 4 years (2021)

Climate Zone 0 (extremely hot):
10,800 < CDD 50°F
Int'l Energy Conservation Code (IECC) adopts for 2018 code

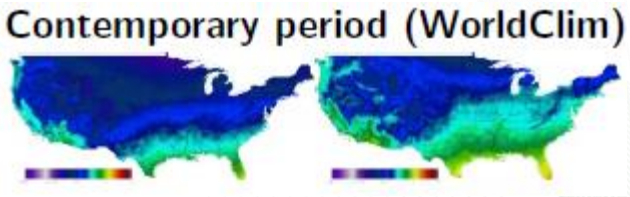
Redefine CZs using model data

- Resolution: 2 km x 2 km grid cells
- Extent: Continental United States
- Present Conditions (1950-2000): WorldClim
- Future conditions (2050, 2100): PCM and Hadley GCMs; for multiple scenarios (IPCC AR4 A1FI, B1)

1. Precipitation during the hottest quarter
2. Precipitation during the coldest quarter
3. Precipitation during the driest quarter
4. Precipitation during the wettest quarter
5. Ratio of precipitation to potential evapotranspiration
6. Temperature during the coldest quarter
7. Temperature during the hottest quarter
8. Sum of monthly Tavg where Tavg >=5 deg C
9. Integer number of consecutive months where Tavg >= 5 deg C (Length of potential growing season)
10. Solar interception
11. Day/night diurnal temperature difference
12. Elevation

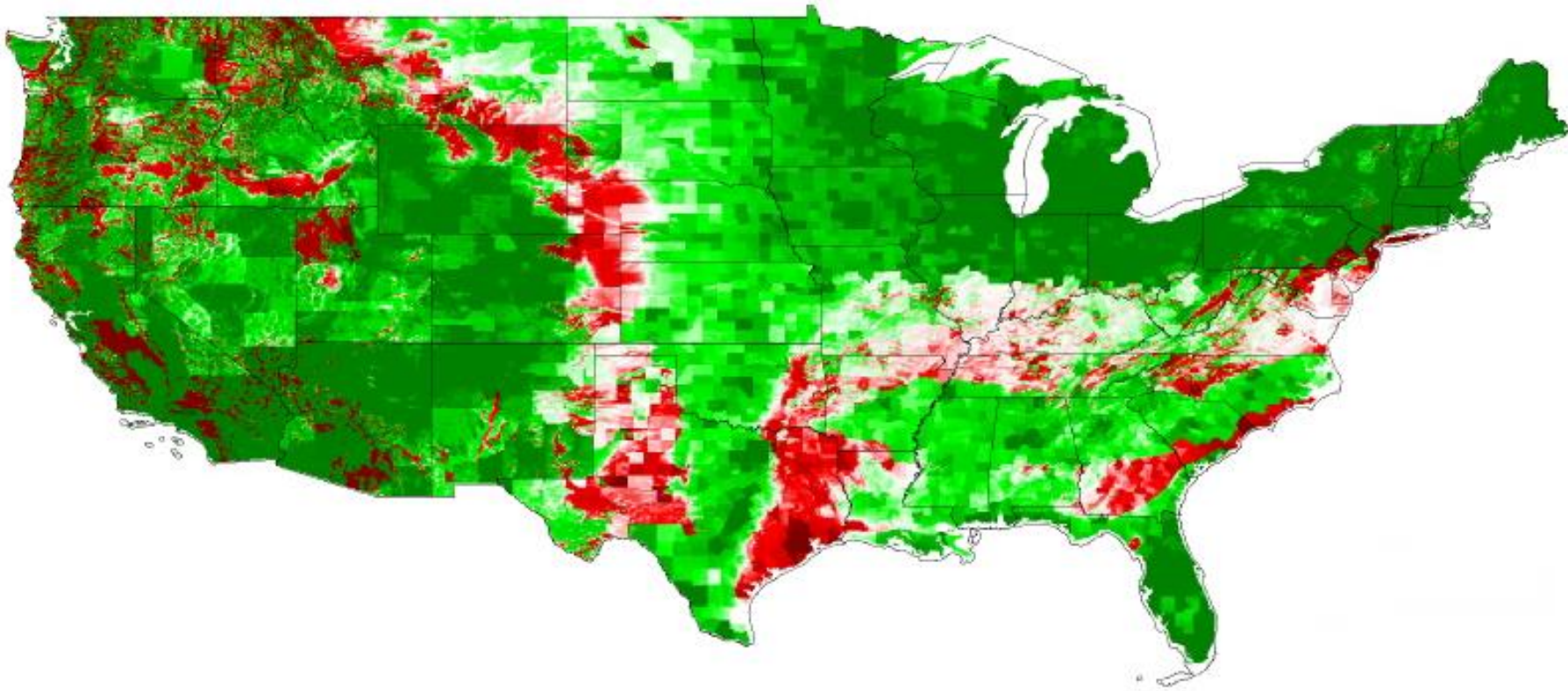


- 12 energy-related variables
  - Temperature
  - Humidity
  - Radiation
  - Elevation



Building-adjusted CZ improvement

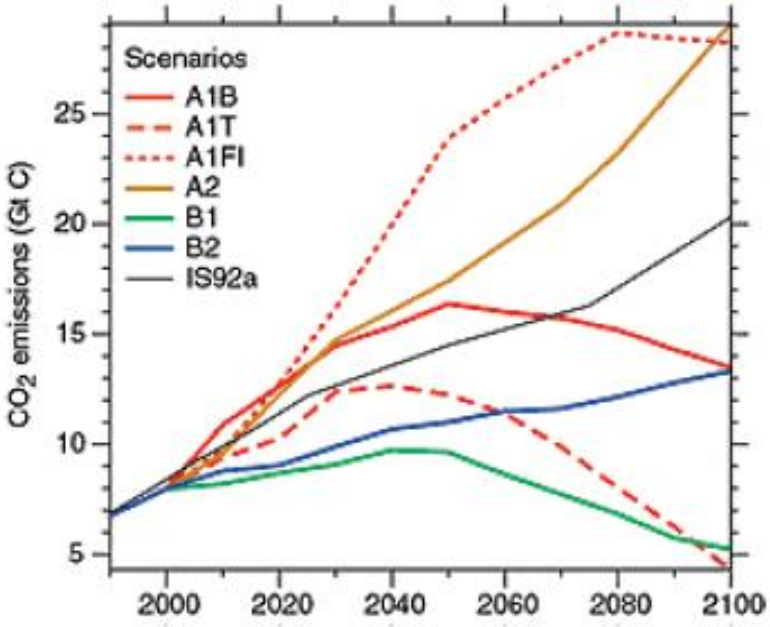
- What other (e.g. political) variables should be included?
- How could the nation's energy security and critical infrastructure resiliency be improved by incorporating future scenarios into the built environment?
- **How much energy and $ could be saved by having a forward-looking climate-aware building code?**

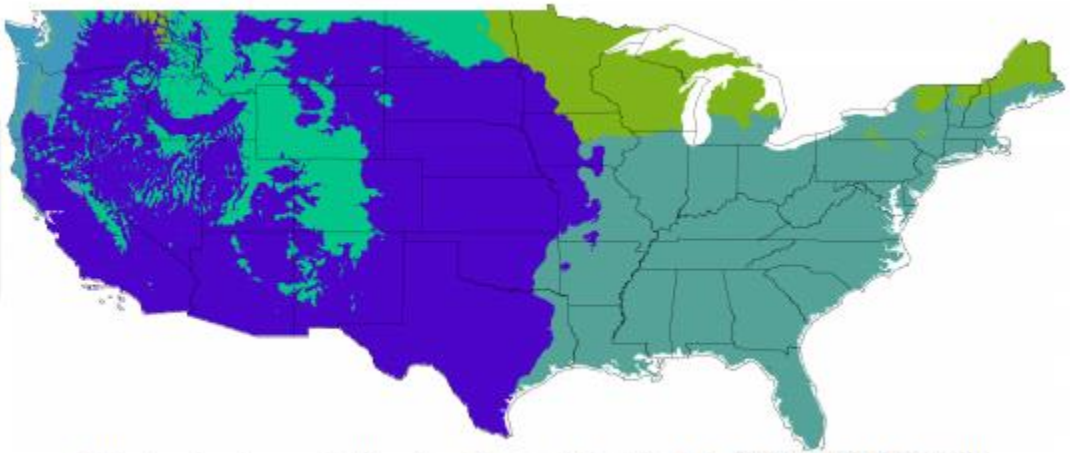


Climate Change Impacts

Contemporary Period

Clustering-based Climate Zones (K=5): HadGCM A1FI 2050





Clustering-based Climate Zones (K=5): HadGCM A1FI 2100

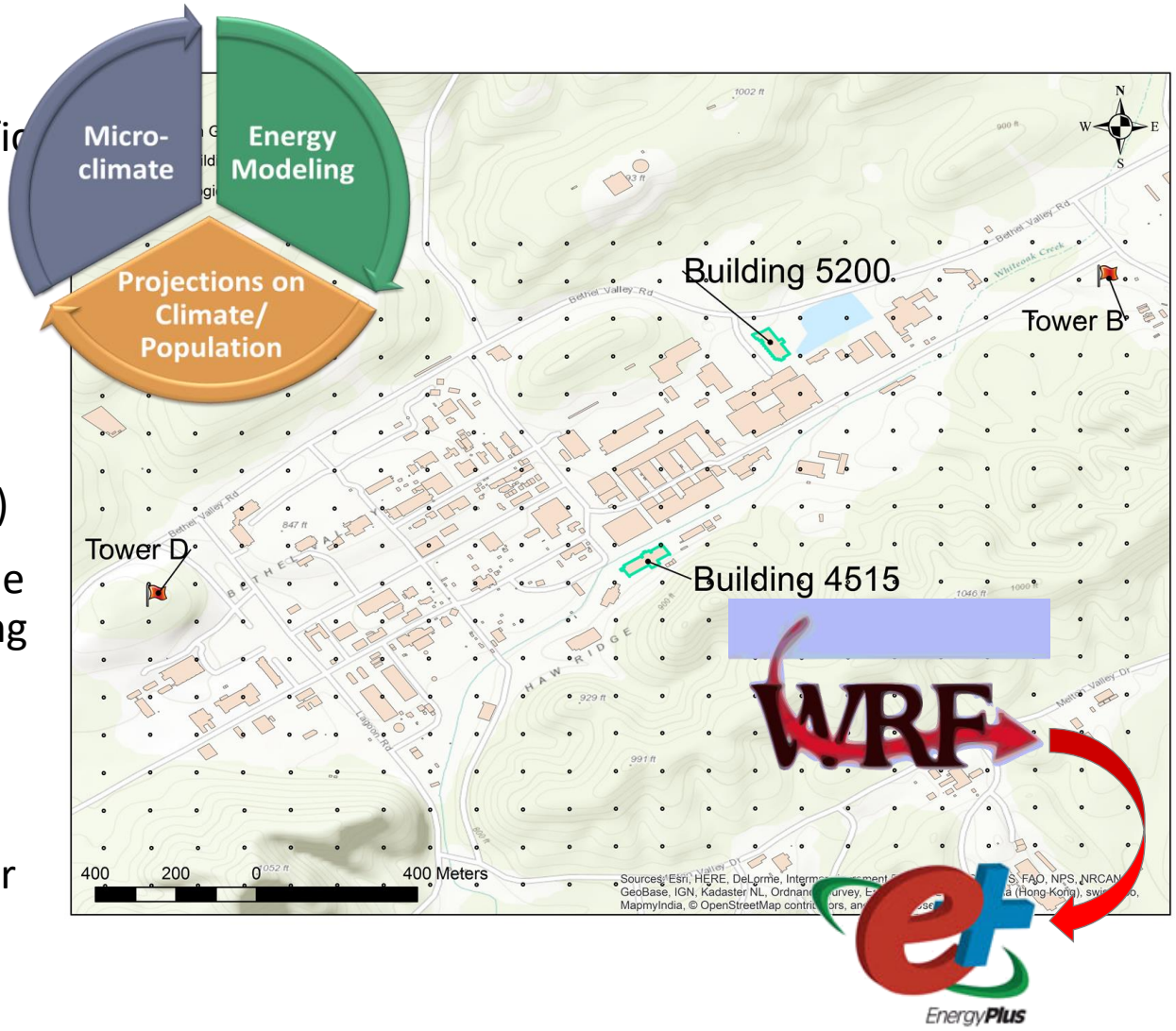
Microclimate

Why Urban Microclimate?

- Rode et al., “Cities and energy: urban morphology and residential heat-energy demand”
  - Neighborhood scale (500m x 500m), residential building type, density (ratio of total floor area to the total grid cell area), building height, surface-to-volume ratio and open space ratio (ratio between unbuilt area and total grid cell area) in cities (urban morphology) **all significantly impact heat-energy demand** for northern latitude (41-53ºN) European cities.
  - Differences in **building topographies** (compact urban block, detached housing, high rise apartments and slab housing) represented among 100 different blocks in the four cities of London, Paris, Berlin and Istanbul **showed significant per-city heat-energy use savings**
    - **11% to 73%** heat energy **savings** from least to most efficient urban **topography**
  - **54 to 83%** heat energy **savings** for different building **densities** (as defined by the sum of the areas of all building floors to that of the sample block area)

Case Study: WRF+EnergyPlus at ORNL

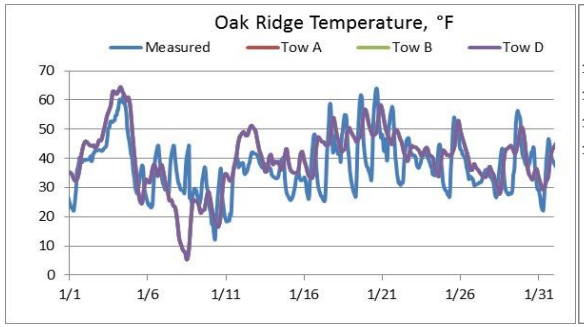
- Weather Research Forecast model (WRF) with site-specific boundary conditions and urban canopy layer for interaction with building geometry
- WRF 3 nested domains to go from 4km^2 to 270-meters to 90-meters (breaking at 1km^2)
- WRF simulation gives multiple weather files for each building
- Weather file couples WRF output to building input
- Future work will couple this with the surface heat transfer coefficients for tighter-coupling at each timestep

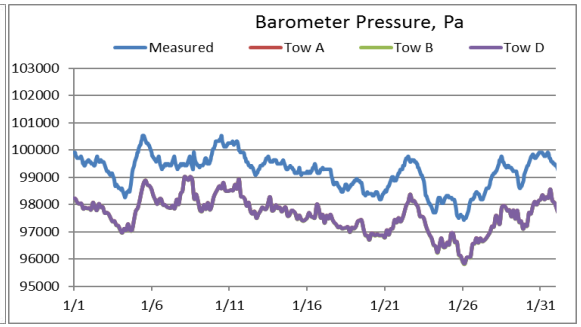


Empirical Validation of WRF

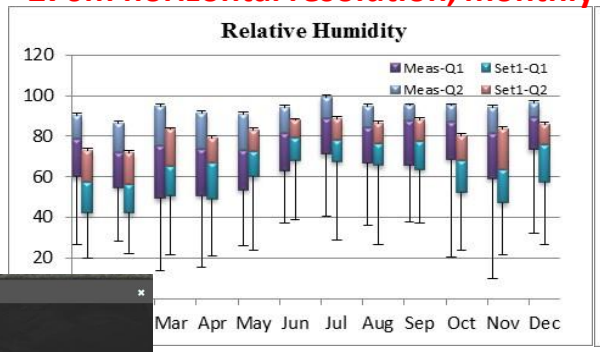
- Daily, monthly, annual statistical characterization
  - Frequency distribution
  - Linear regression
  - ASHRAE Typical Meteorological Year (TMY)
  - Whole building energy analysis
  - Summary and comparison

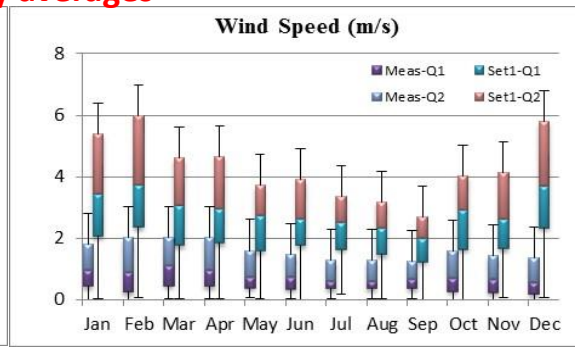
90m horizontal resolution, hourly output



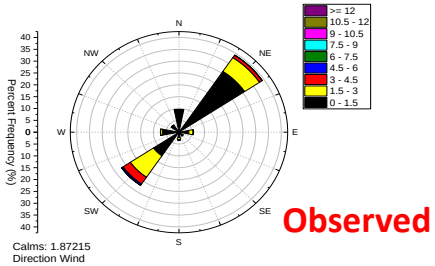


270m horizontal resolution, monthly averages

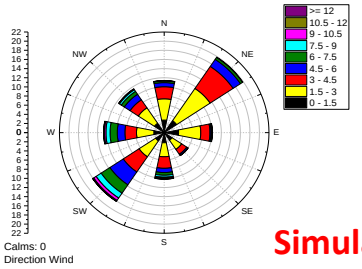




270m horizontal resolution, 2015 annual summary

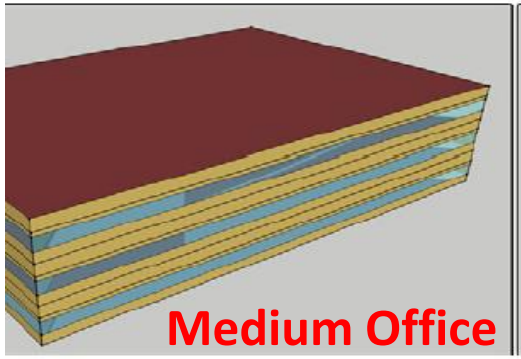


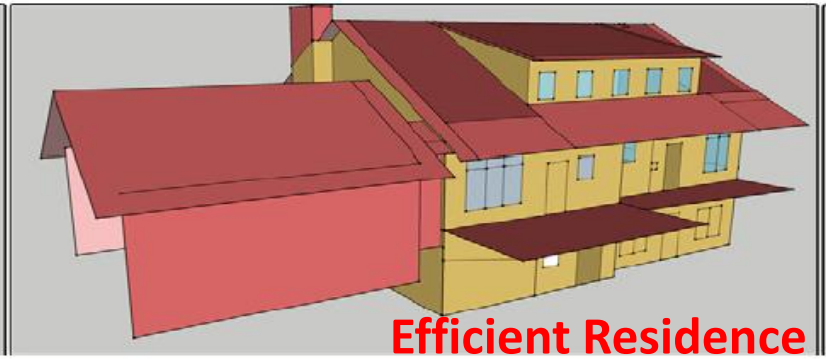
Observed

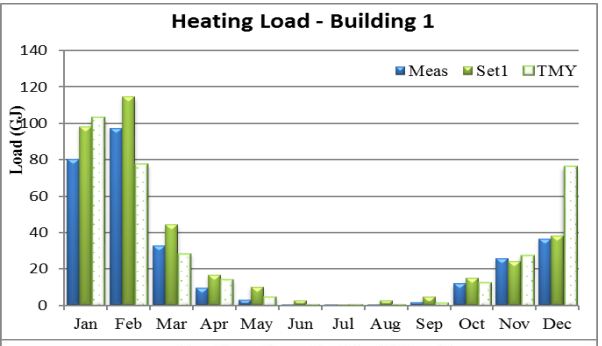


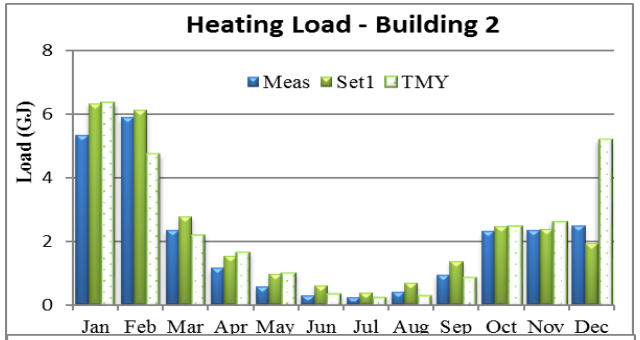
Simulated

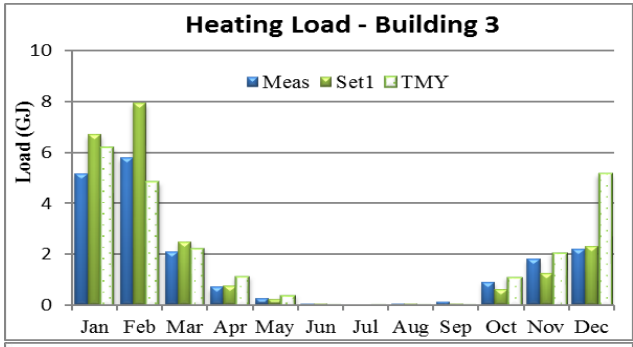
Microclimate impact on building loads

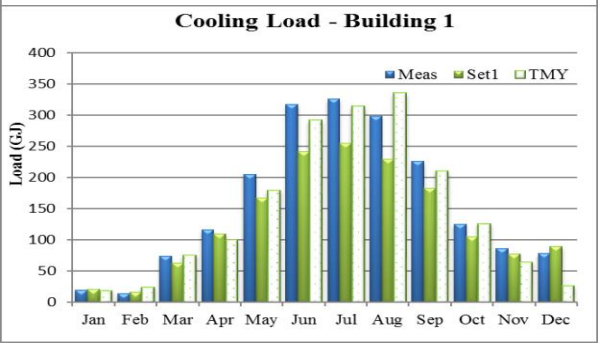


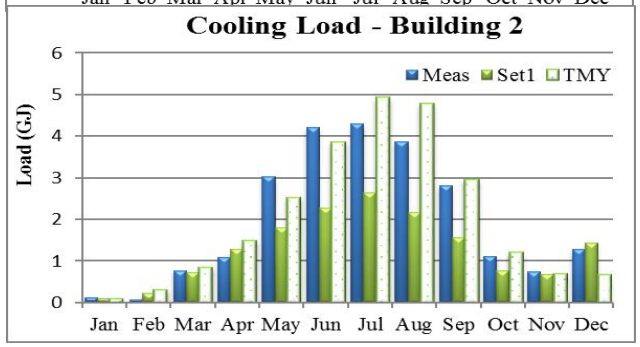


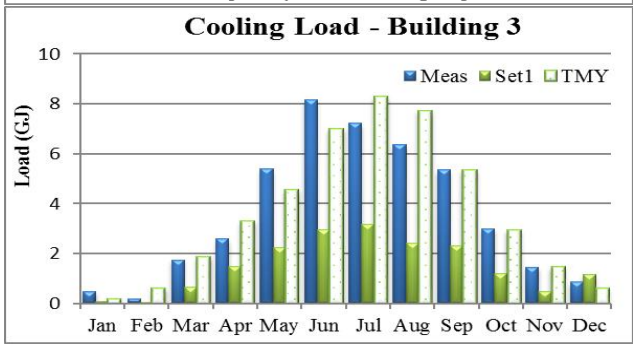




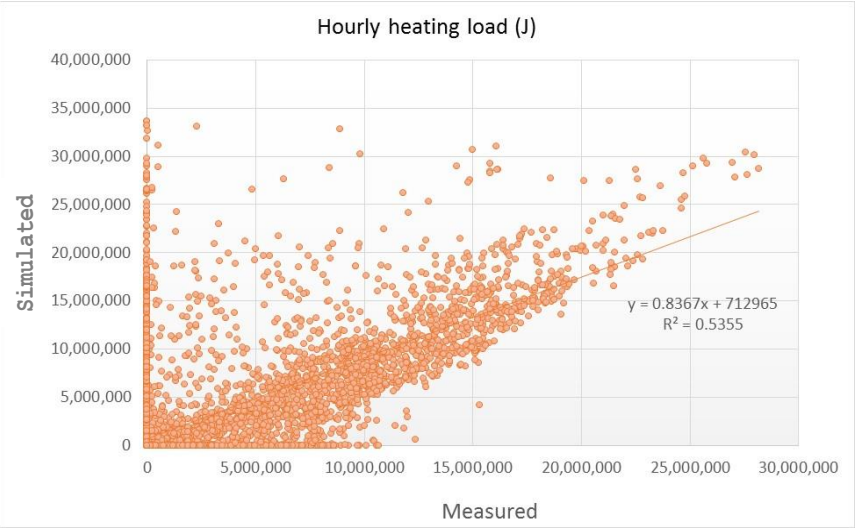


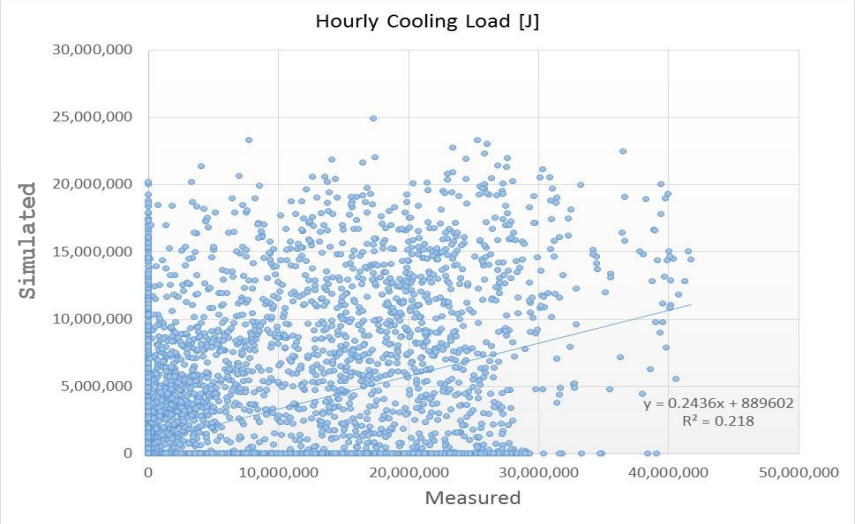




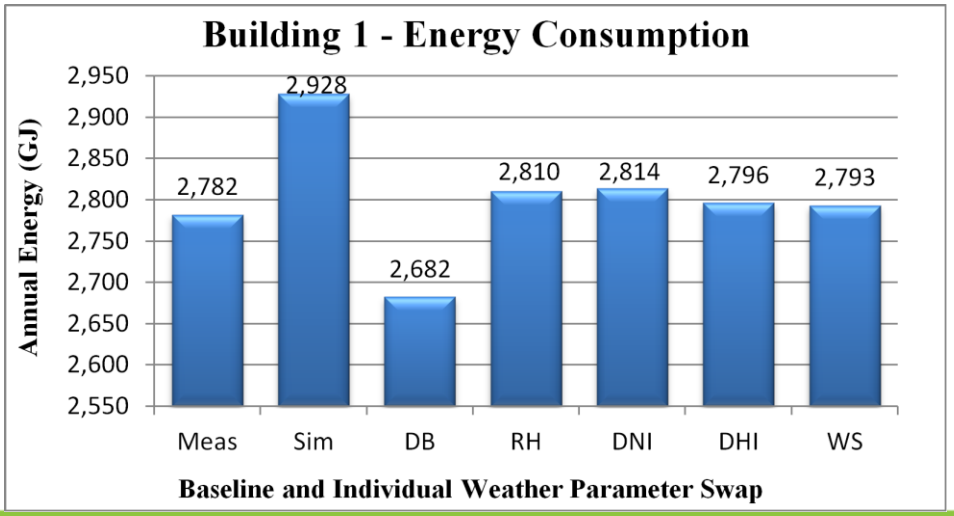


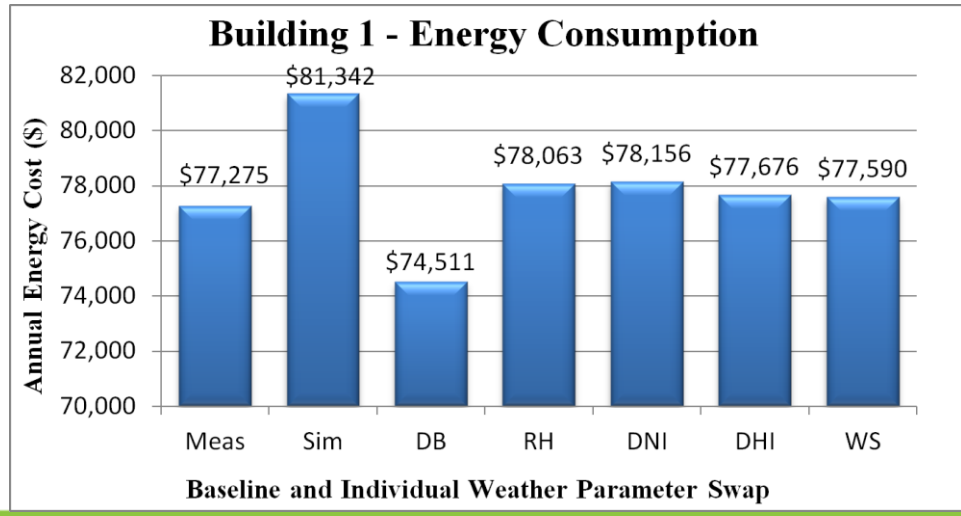
Microclimate – 5% ($4k/yr) energy difference





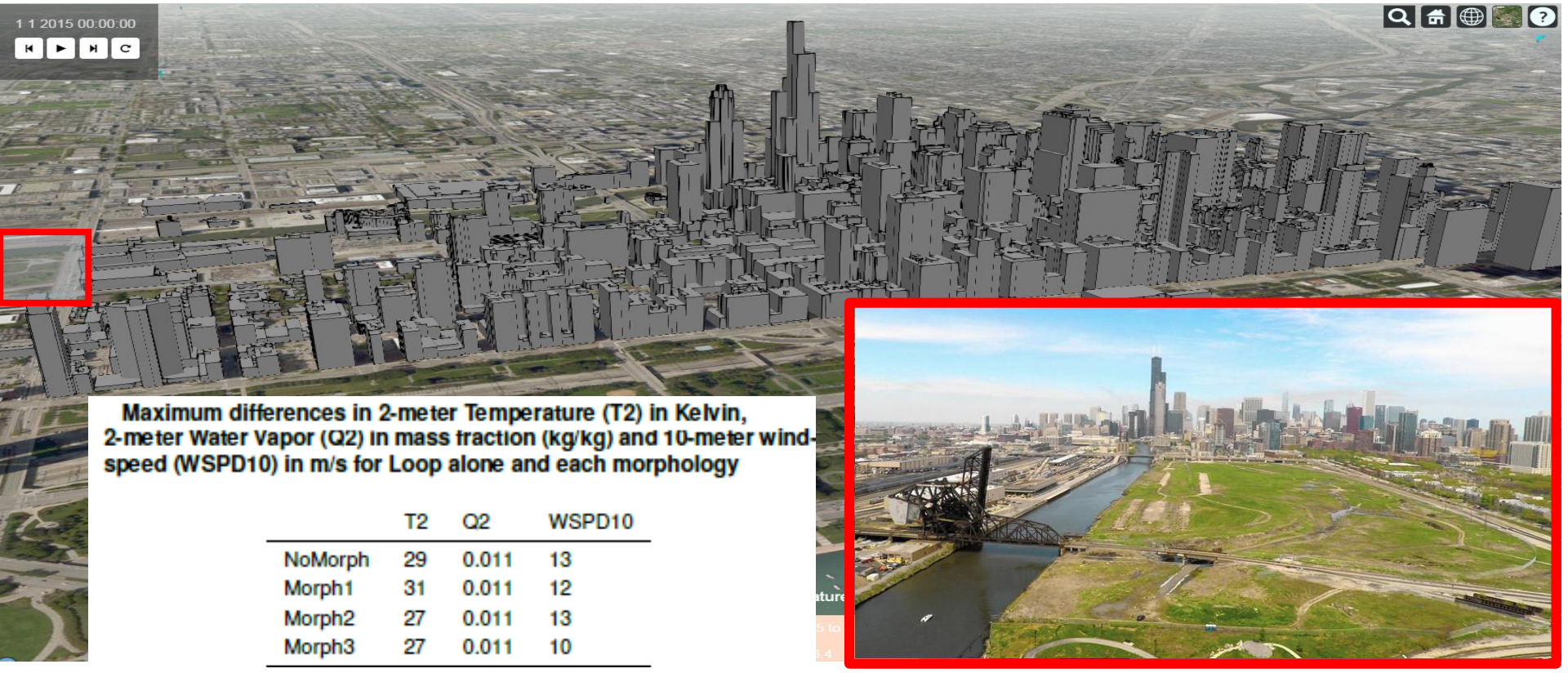
Hourly heating and cooling loads





Chicago

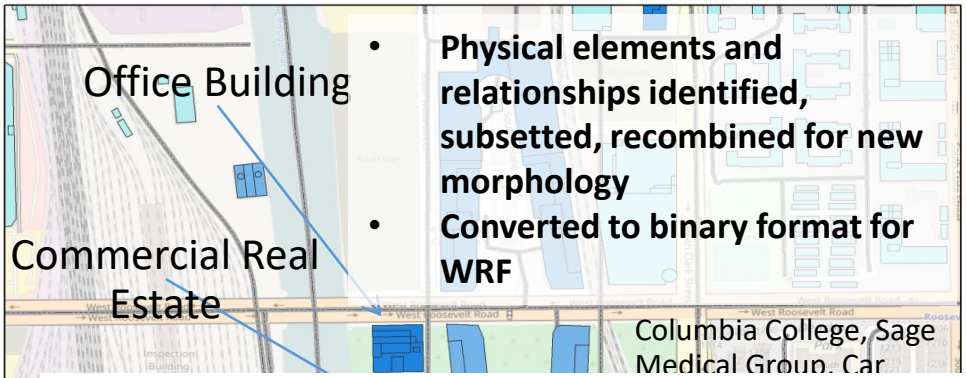
- Urban planning for redevelopment of an area south of the Chicago loop
- Microclimate impacts on downtown Chicago, electrical planning, transportation



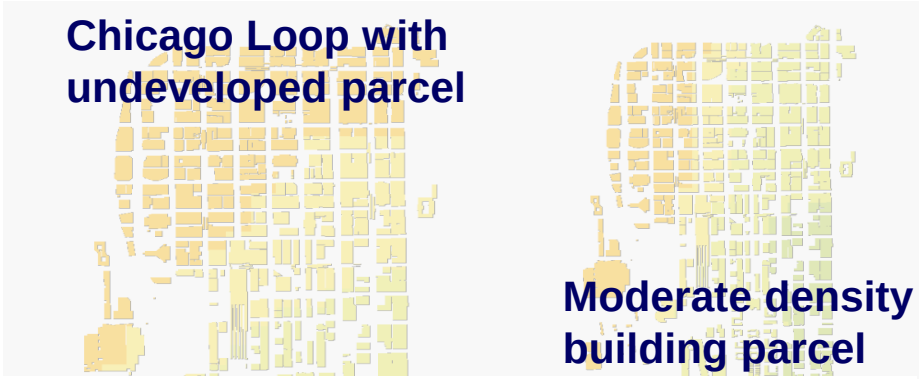
Maximum differences in 2-meter Temperature (T2) in Kelvin, 2-meter Water Vapor (Q2) in mass fraction (kg/kg) and 10-meter wind-speed (WSPD10) in m/s for Loop alone and each morphology

	T2	Q2	WSPD10
NoMorph	29	0.011	13
Morph1	31	0.011	12
Morph2	27	0.011	13
Morph3	27	0.011	10

Urban Microclimate



- Physical elements and relationships identified, subsetted, recombined for new morphology
- Converted to binary format for WRF



	No. of Bldgs	Area (m^2)	Elec (GJ)	Gas (GJ)	EUI elec (GJ/m^2)	EUI gas (GJ/m^2)
NoMorph	334	19,924,975	5,587,504	3,728,528	0.2804	0.1871
Morph1	361	20,892,217	6,025,625	4,754,649	0.2884	0.2276
Morph2	355	22,996,771	6,414,792	4,989,149	0.2789	0.2169

Best EUI:
High Density

Virtual Utility

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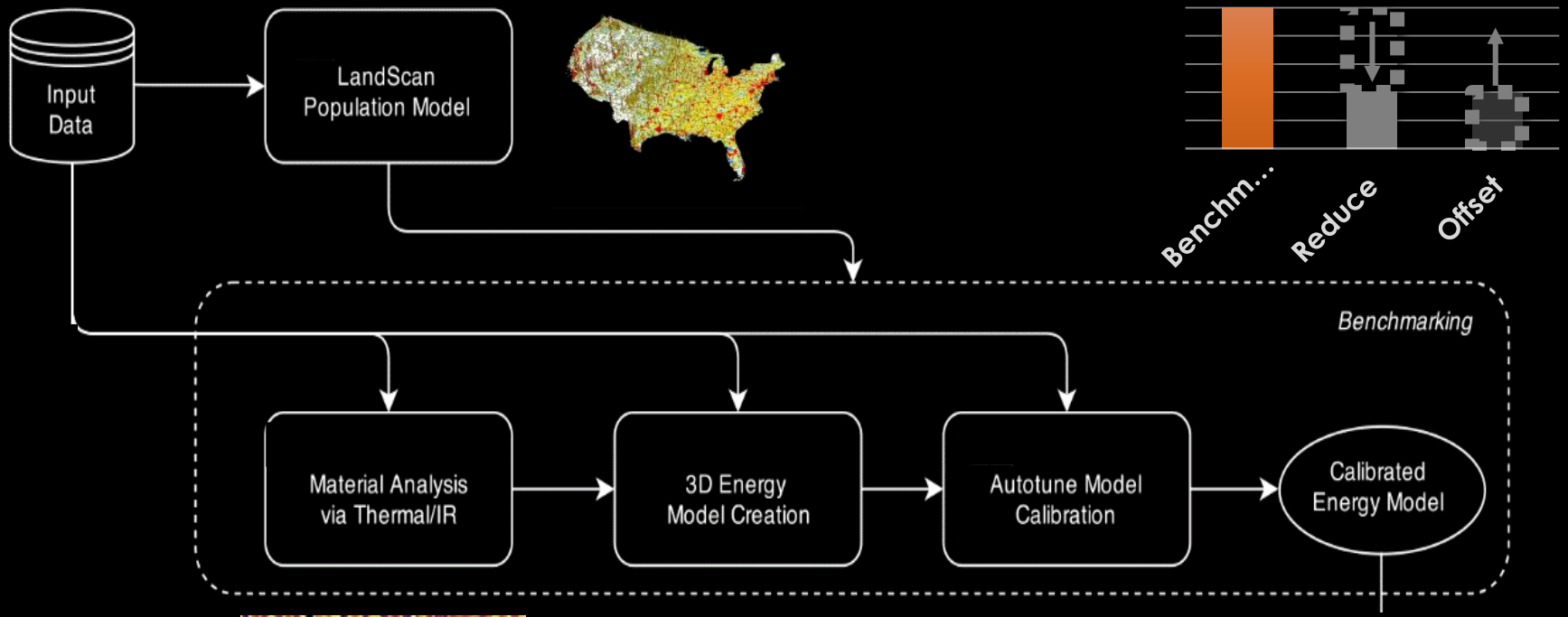
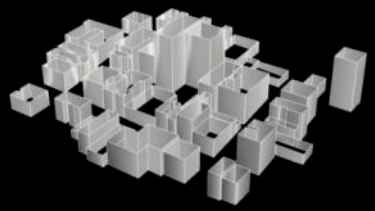
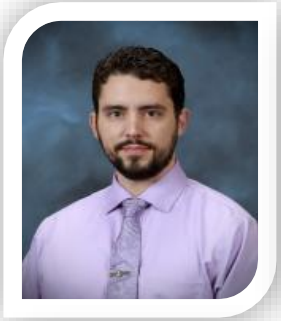
Model America 2020 – calibrated BEM for every U.S. building





Acknowledgements

- U.S. Department of Energy
- National Nuclear Security Administration
- Oak Ridge National Laboratory
- Building Technologies Office
- Office of Electricity











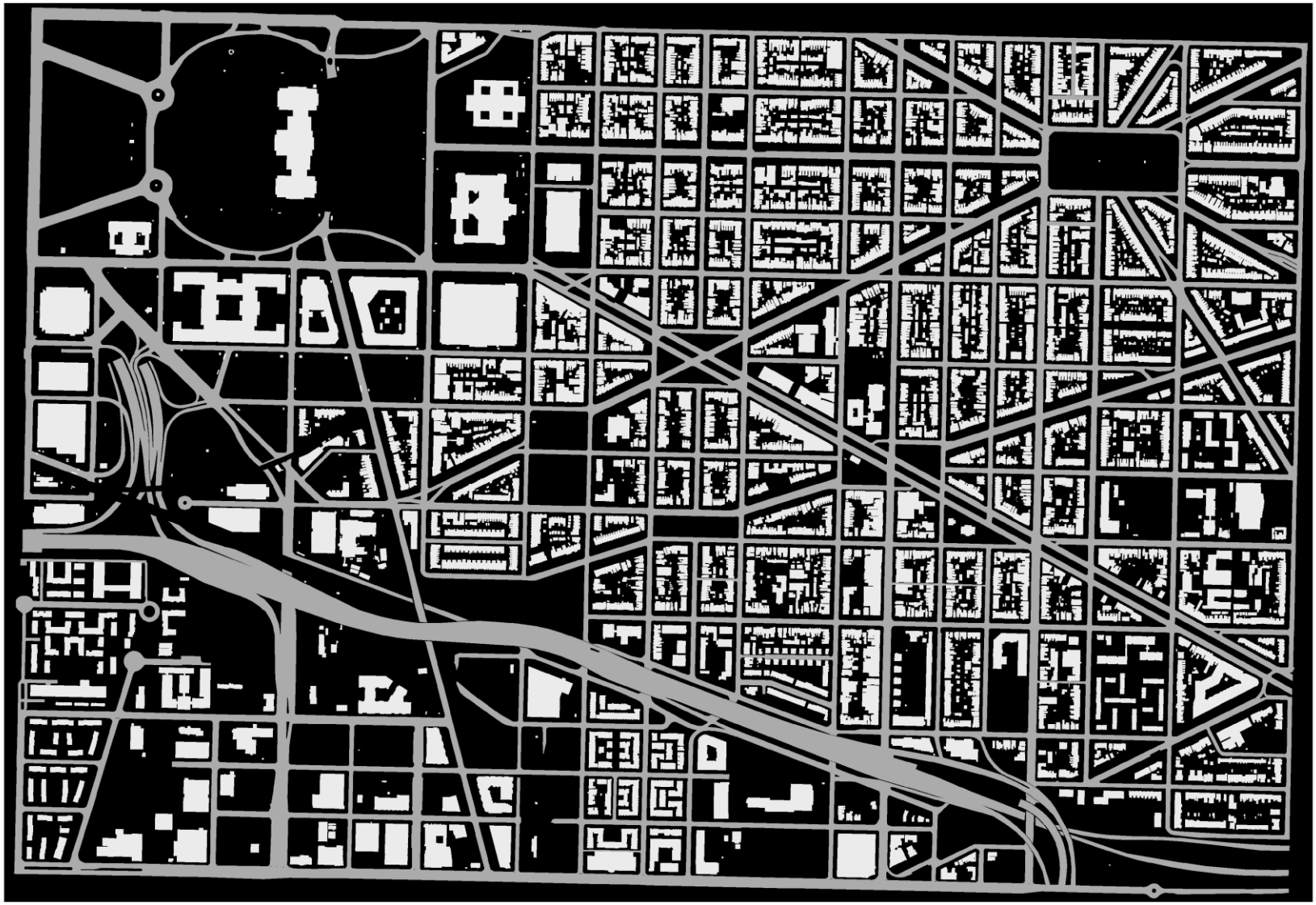



Data Sources

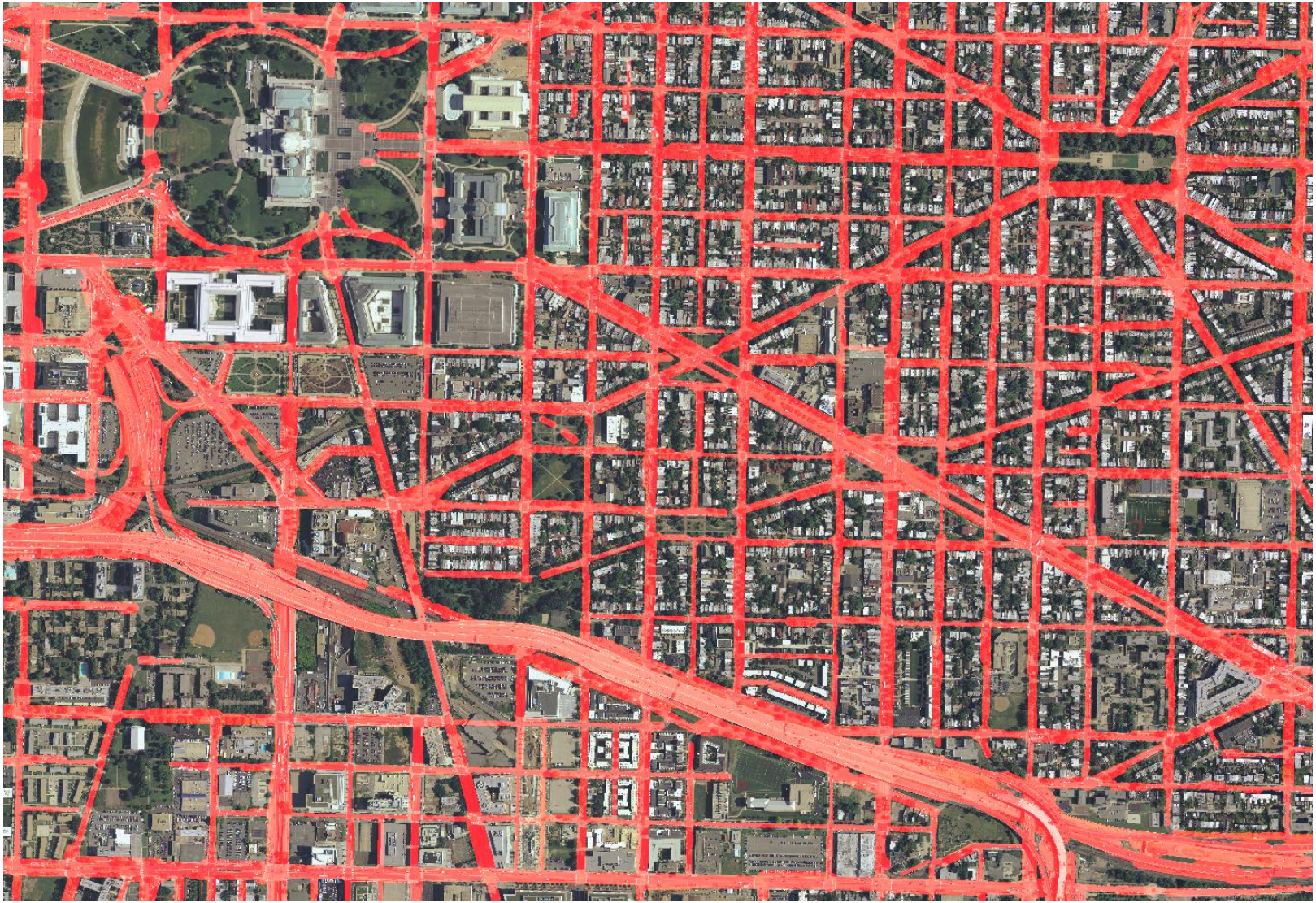
- Database and image sources for urban model generation
  - Satellite and airborne imagery
  - Cartographic data
  - Ground level images
  - Elevation data
  - Building information databases
  - 3D building model databases

	Short Title
Summary	Satellite imagery, including panchromatic and multispectral images
Data type	Image
Company	
Website	
Temporal resolution	Cities - 3-11 times per week
Spatial resolution	0.3 m
Measure accuracy	
Cost	$11 per sq. km
Format	GeoTiff
Mapping to building input variables	Building footprints
Mapping to area properties	Vegetated areas, road surface, buildings, parking lots
Mapping to material properties	Road pavement materials (e.g., concrete, asphalt), parking lots (e.g., gravel, soil)
Coverage of US	Over 10 million km^2 of coverage of the contiguous US
Orientation	Aerial
Existing internal software	N/A
Existing expertise	Remote sensing data analysis tool
Restrictions	N/A
Comments	

Manual Segmentation of DC



Automatic Road Extraction

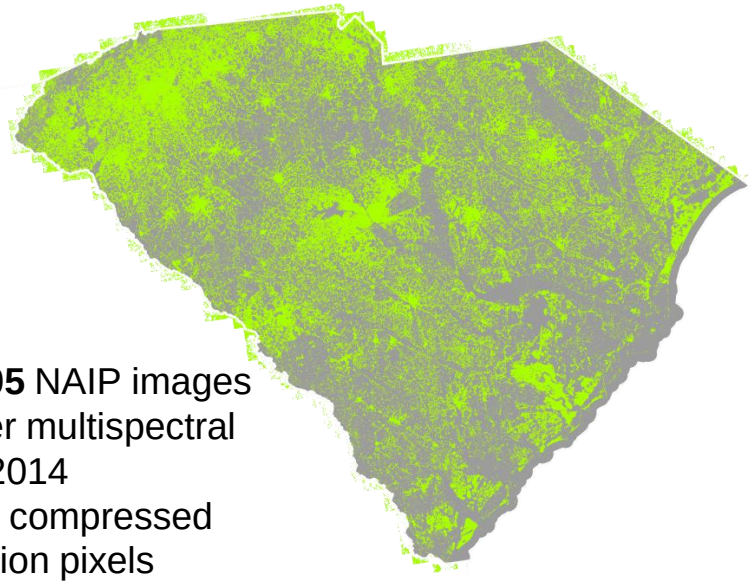


Automatic Building Footprint Extraction

Algorithm: Deep Learning extended and using GPUs for fast building footprint and area extraction over large geographical areas.

Multi-company Competition Precision/Recall – 30/35; Current Precision/Recall – 60+/60+

Automatic Building Footprint Extraction



- **220,005** NAIP images
- 1 meter multispectral
- 2012-2014
- 5.8 TB compressed
- 9.8 trillion pixels

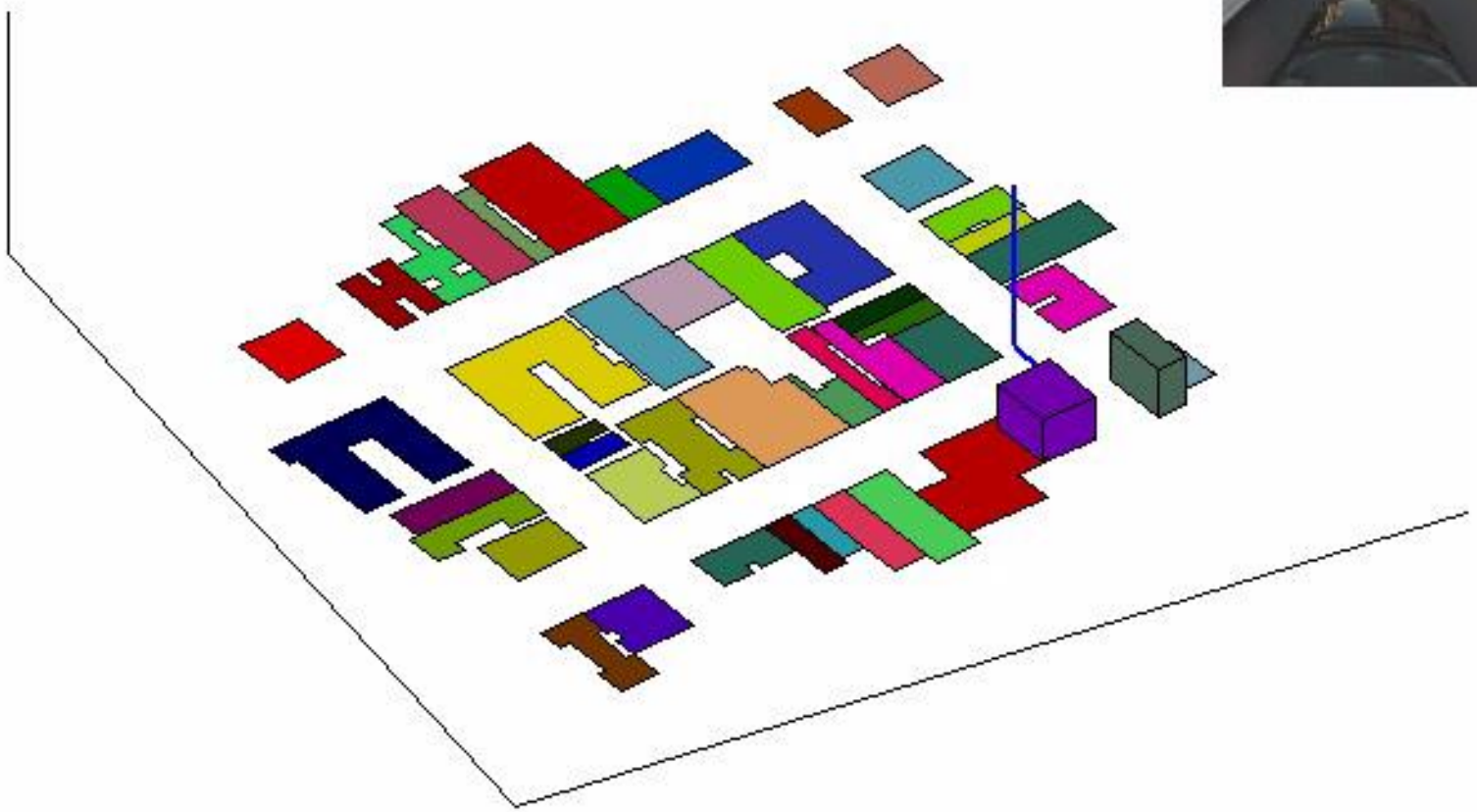
Portland, OR (25,393 m²)
Imagery: June – July 2012
Lidar: September 2010

Frankfort, KY (14,801 m²)
Imagery: June 2012
Lidar: June 2011

Part of Knox County, TN (18,527 m²)
Imagery: June 2012
Lidar: October 2014

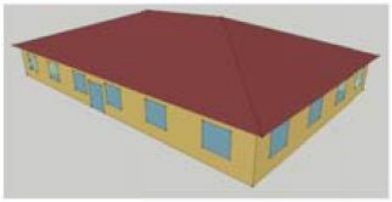
Processing Street-Level Imagery

3D Building Model Generation

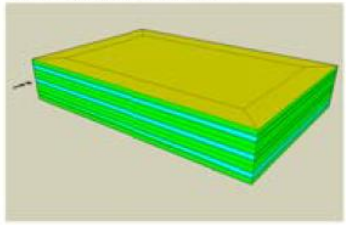


Prototype Buildings

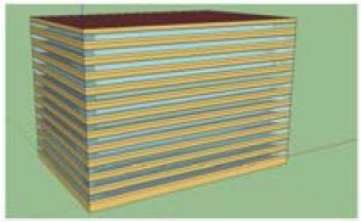
Small Office



Medium Office

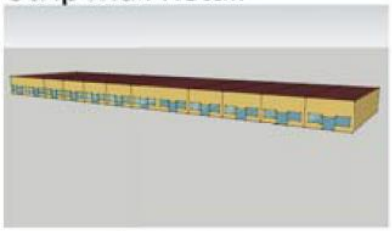


Large Office

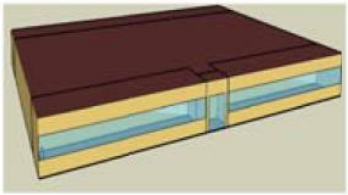


Warehouse

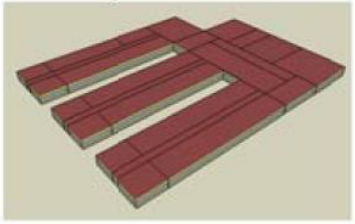
Strip Mall Retail



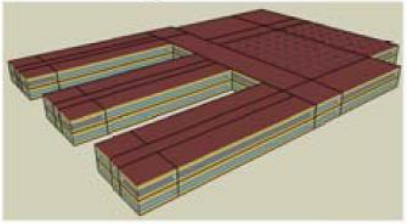
Standalone Retail



Primary School

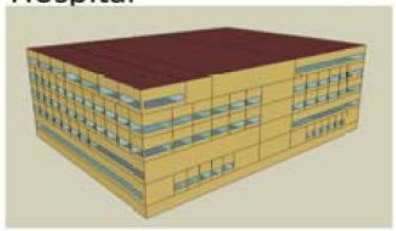


Secondary School



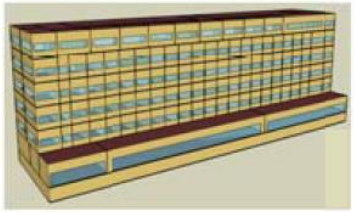
Outpatient Healthcare

Hospital

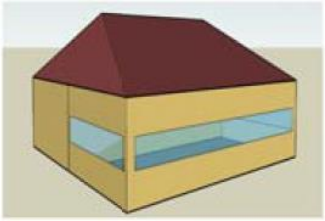


Small Hotel

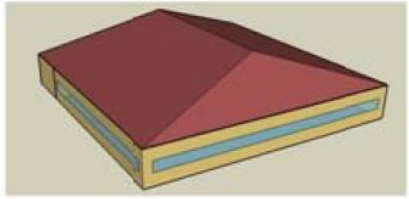
Large Hotel



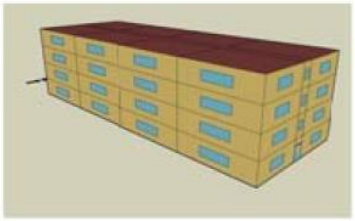
Quick-service Restaurant



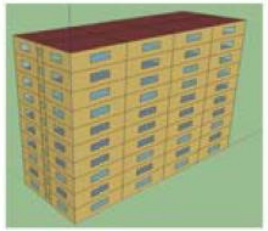
Full-service Restaurant



Mid-rise Apartment



High-rise Apartment



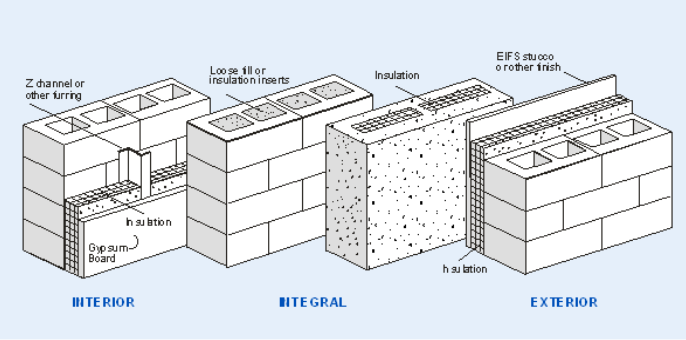
Prototype and Reference Building Updates

- 70, 80 → 90% of U.S. commercial floor space
- 16 types, 16 climate zones, 3 vintages = 768 buildings
  - 17-19+ types, 16-17 climate zones, 5-16+ vintages = 1,360-5,168 models
- ~3,000 avg. parameters per building
  - Square footage, HVAC layout, infiltration (i.e. airflow)
  - Construction (e.g. wall, layers of envelope)
  - Material properties (ASHRAE Handbook of Fundamentals)
  - Equipment and occupancy schedules

Physical Properties of Materials 33.3

Table 3 Properties of Solids

Material Description	Specific Heat, Btu/lb·°F	Density, lb/ft³	Thermal Conductivity, Btu/h·ft·°F	Emissivity Ratio	Emissivity Surface Condition
Aluminum (alloy 1100)	0.214[b]	171[u]	128[u]	0.09[u]	Commercial sheet
				0.20[u]	Heavily oxidized
Aluminum bronze (76% Cu, 22% Zn, 2% Al)	0.09[u]	517[u]	58[u]		
Asbestos: Fiber	0.25[b]	150[u]	0.097[u]		
Insulation	0.20[t]	36[b]	0.092[b]	0.93[b]	"Paper"
Ashes, wood	0.20[t]	40[b]	0.041[b] (122)		
Asphalt	0.22[b]	132[b]	0.43[b]		
Bakelite	0.35[b]	81[u]	9.7[u]		
Bell metal	0.086[t] (122)				
Bismuth tin	0.040*		37.6*		
Brick, building	0.2[b]	123[u]	0.4[b]	0.93*	



AutoBEM – Automatic Building detection and Energy Model creation

- 19 underlying Intellectual Properties (granted or in process)
  - Range from classified to open-source
  - AutoBEM-LiDAR
  - AutoBEM-Aerial – world's best building footprint extractor
  - AutoBEM-Street
  - AutoBEM-3D DB
  - AutoBEM-Type
  - AutBEM-Gen – world's fastest BEM creator
  - AutoSIM – world's fastest buildings simulator
  - AutoDoEGen
  - AutoSTAT
  - Autotune – world's best calibration algorithm

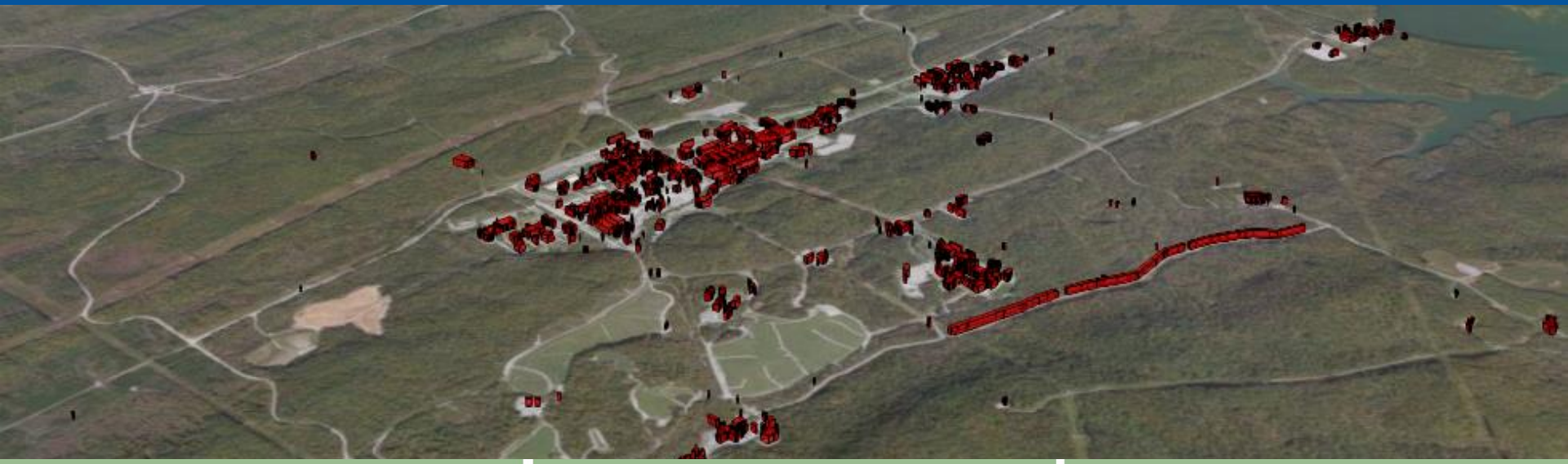
AutoBEM – ongoing work

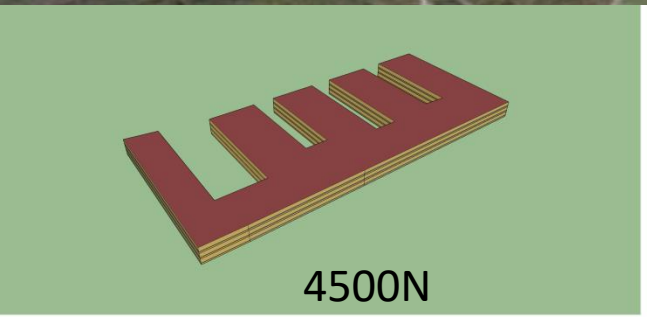
- AutoBEM-Aerial/HVAC
- AutoBEM-Aerial/Chiller
- AutoBEM-scrape

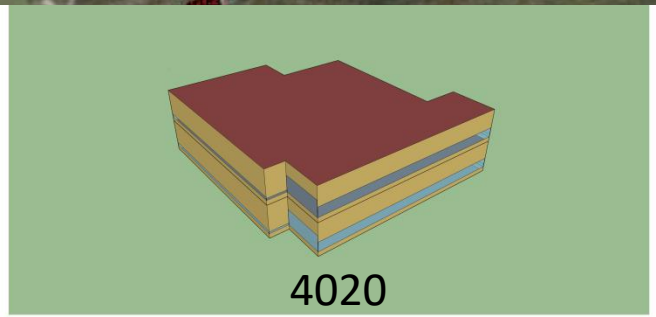
AutoBEM Façade

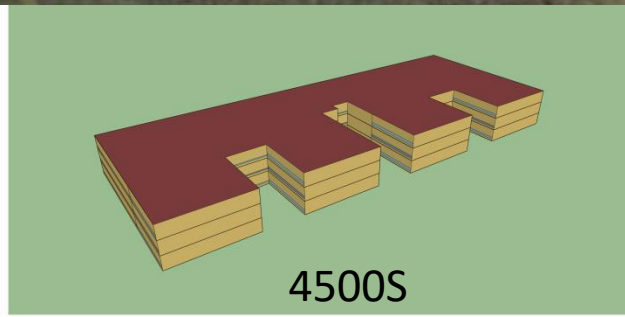
AutoBEM WWR

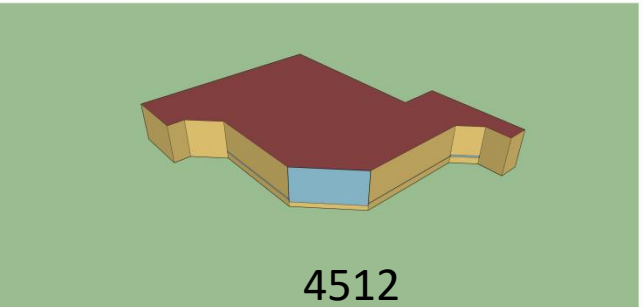
Oak Ridge National Laboratory

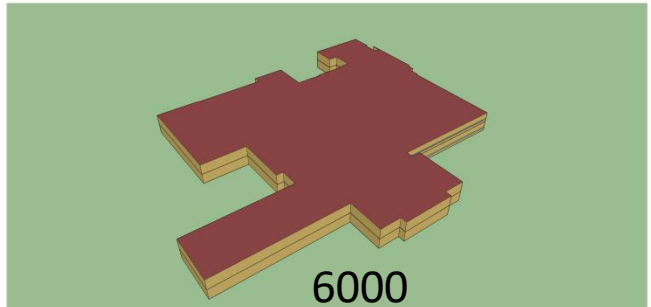


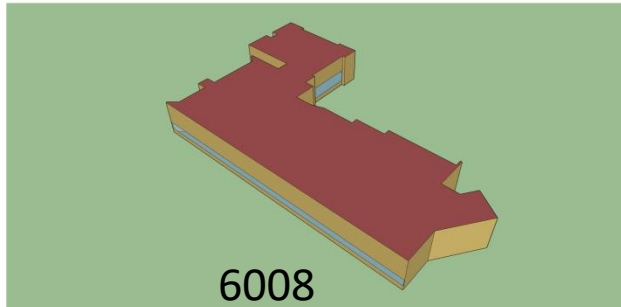






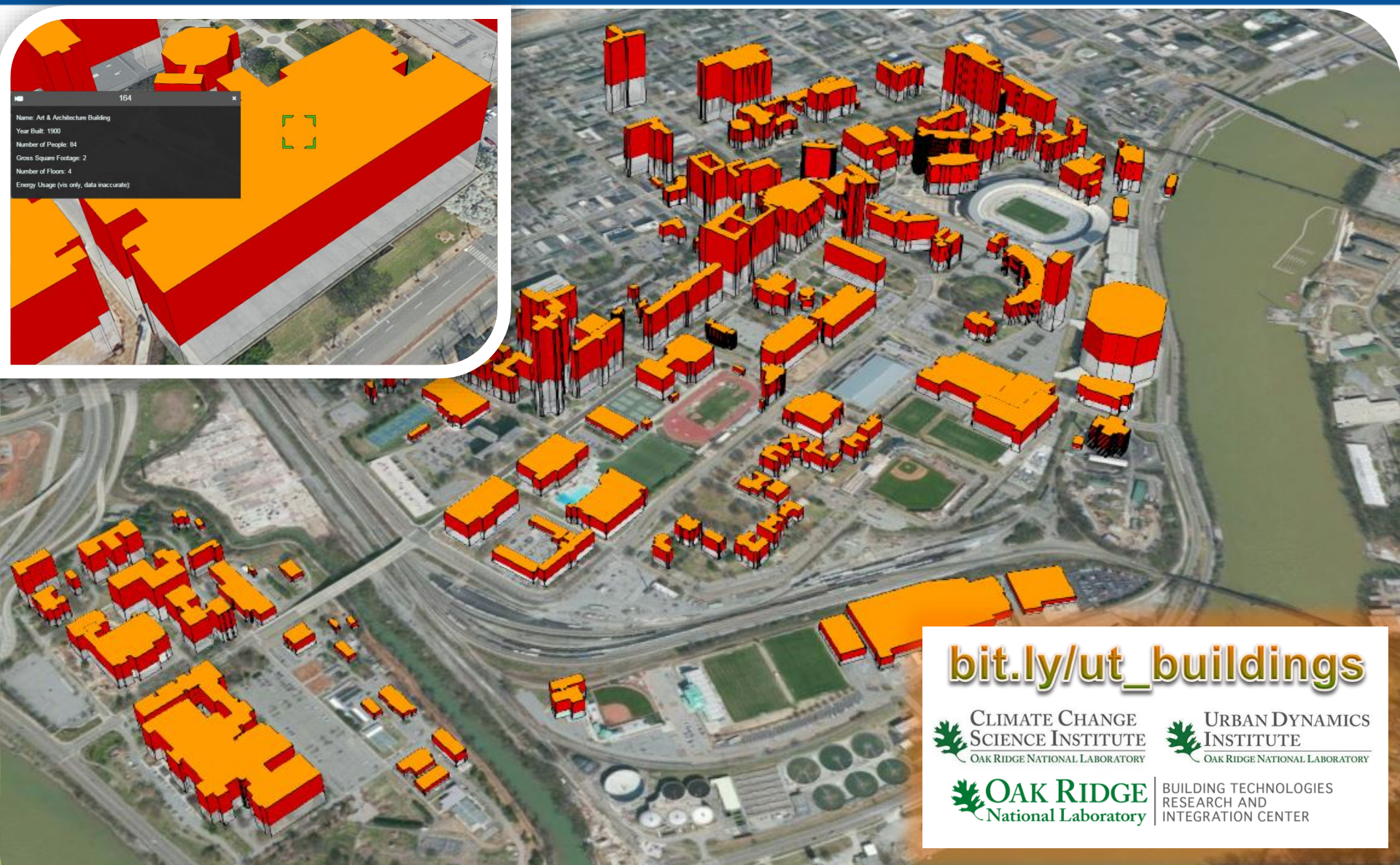




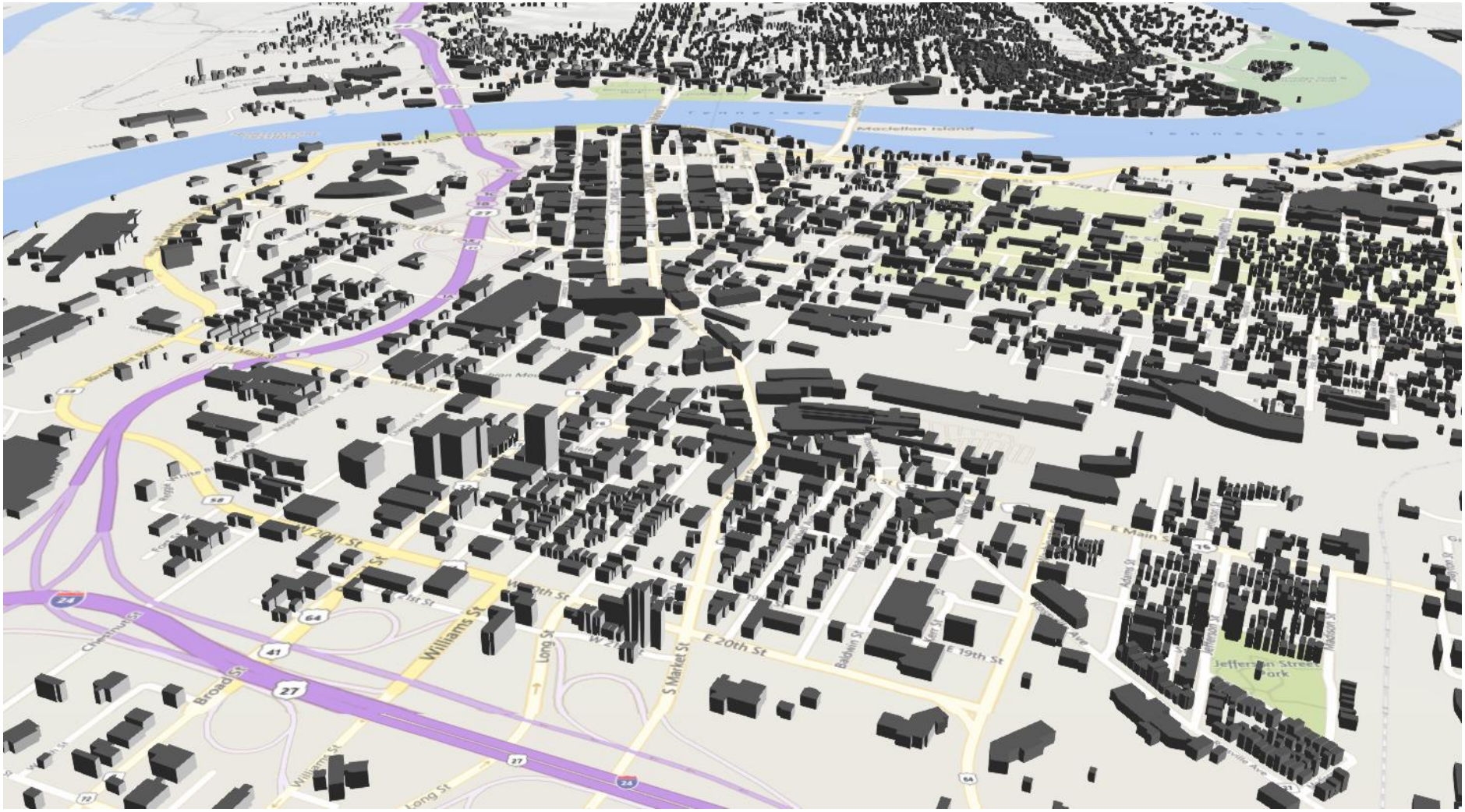


Oak Ridge National Laboratory (interactive)

The University of Tennessee (2 days)



Chattanooga, TN (100,000+ buildings)



The AutoBEM technology "axe"

135,481 building models have been created and matched to EPB's PremiseID

Limitations: limited building types, not calibrated, will improve quarterly

QA/QC: will show how close our simulations are to 15-min data

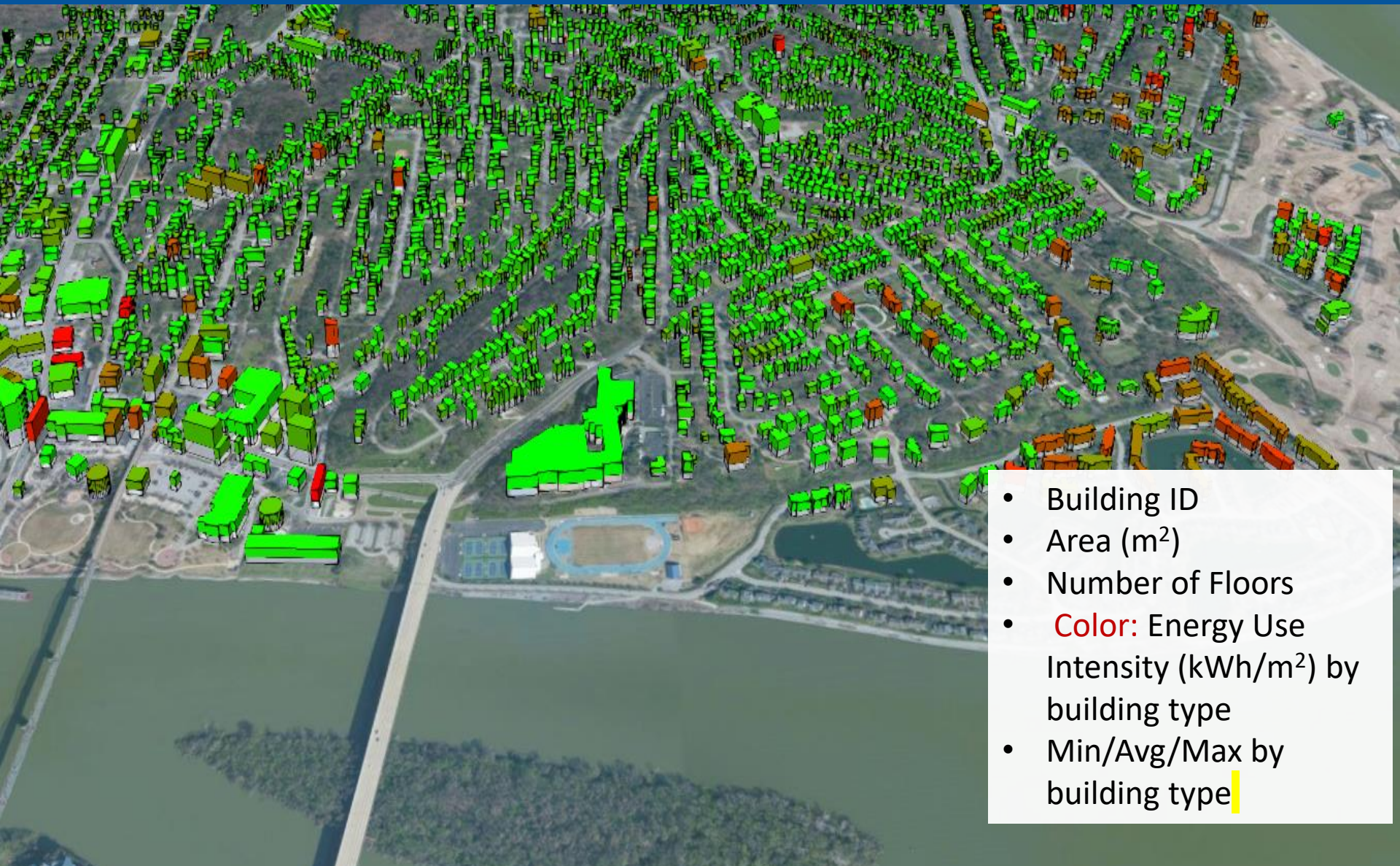
1.9 million EnergyPlus building energy models using AutoBEM technology, Titan, cloud, and local servers to produce and analyze 10.7 TB of simulation data.

1. Generate baseline building – OpenStudio (1.5-3h Amazon, 30h internal)
2. Run ECM measures – OS Measure (30 mins AWS, 2h internal), Custom (1m AWS, 5m intl.)
3. Copy data to Titan – 1 min (1.2GB tar.gz)
4. Submit to Titan – 0-2 hours in queue
5. EnergyPlus simulation time – 30-45 mins (5mins/sim = 1.4 years to simulate EPB on 1 core)
6. Data transfer – 40 mins (160GB tar.gz)
7. Uncompress – 10-15 mins
8. Reformat data – 20-30 mins
9. Analysis – 5-10 mins

Time for creation, annual simulation, and analyzing "all" EPB buildings

6.5 hours (6.1h –36.5h)

1a – Peak contribution percentile by type



- Building ID
- Area (m^2)
- Number of Floors
- Color: Energy Use Intensity (kWh/m^2) by building type
- Min/Avg/Max by building type

Virtual EPB – interactive results

60246

ID	60246
DOE Building Type	SmallOffice
Num Floors	3
Percentile	87.70 %
Estimated wholesale vs retail cost	$ 9797.07
CO2 emissions	222052.32 lbs/year
Smart Thermostat - 4F cost savings	$ 1316.61
Smart Thermostat - 8F cost savings	$ 2325.84
TMY->AMY Smart Thermostat - 4F cost savings	$ 204.99
TMY->AMY Smart Thermostat - 8F cost savings	$ 103.41
HVAC Efficiency ECM	$ 1291.79
Gas HVAC ECM	$ 4276.69
Gas Water Heater ECM	$ 725.58
Heat Pump Water Heater ECM	$ 476.95
Insulation ECM	$ 736.27
Infiltration ECM	$ 1577.50
Lighting ECM	$ 2898.95

Discussion

Joshua New, Ph.D., CEM, PMP, CMVP

BTRIC, Software Tools & Models

Oak Ridge National Laboratory

newjr@ornl.gov

HPC Tools for Modeling and Simulation

Capturing building energy consumption