Assessing the Role of Buildings in Sustainable Urban Eco-Systems

Jelena Srebric, Ph.D.
Cluster for Sustainability in the Built Environment
Mechanical Engineering Department, University of Maryland
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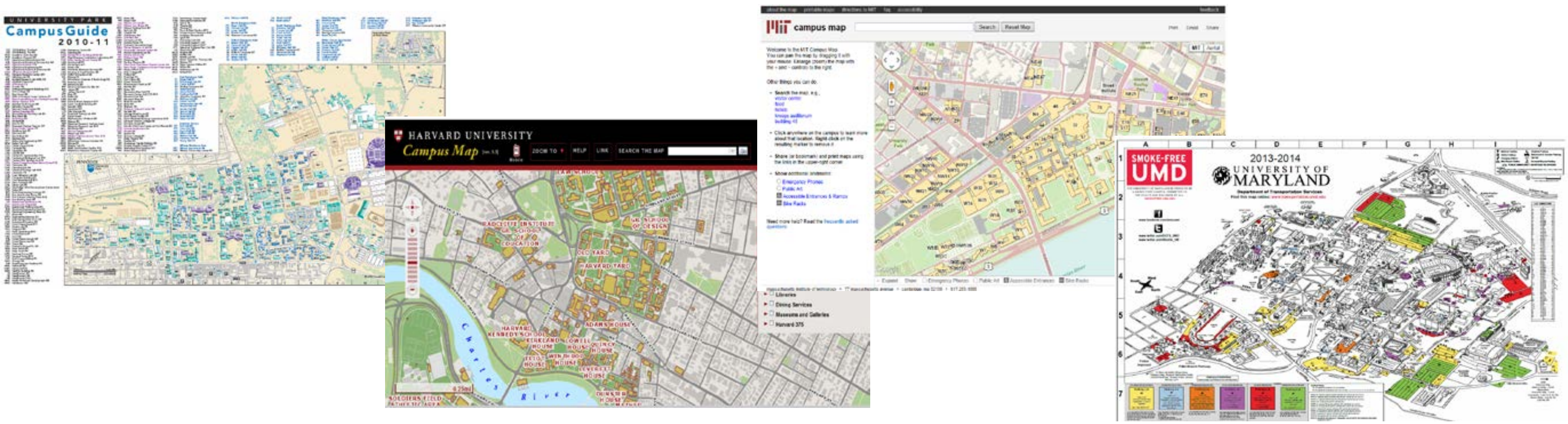
Research: Vision

The EFRI-SEED PULSE project focuses on **energy flow in urban environments** at a neighborhood scale and connects the energy consumption to **occupant comfort perceptions and health outcomes**.



Campus sustainability and/or stewardship offices at Penn State, Harvard, MIT and University of Maryland.

Research: Expected Legacy

The NSF EFRI PULSE project is developing:
(1) tools,
(2) procedures, and
(3) guidelines
to enable innovations for design, operation, and renovation of new and existing **building structures at university campuses**.

Examples of deliverables in each category:

(1) VirtualPULSE, UMI, Memo Machines

(2) Data from case studies, design performance metrics

(3) Adaptation guidelines

Research: Objectives

1. Develop **urban modeling platforms** to identify and test opportunities for more sustainable cities and neighborhoods.
2. Develop **new physical models** for the urban modeling platforms to increase accuracy of building energy simulations and enable analyses of comfort/health outcomes for occupants.
3. Assess individual buildings' effects on energy consumption of surrounding **clusters of buildings** , and promote development of sustainable neighborhoods via quantitative analyses.
4. Identify and characterize a relationship between the sustainable built environments and **occupant comfort/health.**
5. Develop a data driven thermal sensation and comfort model that uses occupants' feedback. Based on the model, state-feedback thermal **control algorithms** are designed.

Research: Overview

Urban Modeling Platforms

New Physical Models

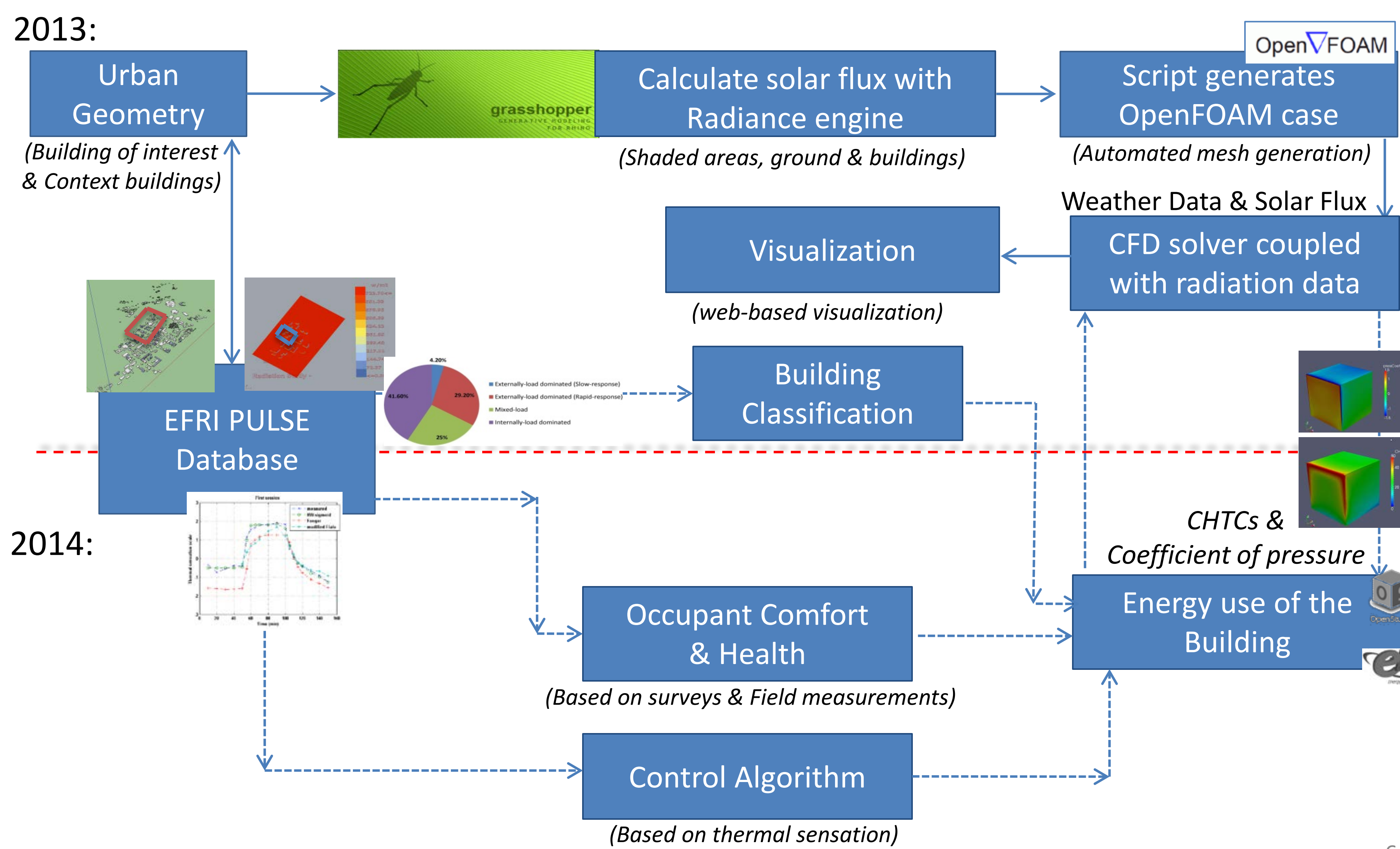
Energy in Building Clusters

Occupant Comfort/Health

Control Algorithms

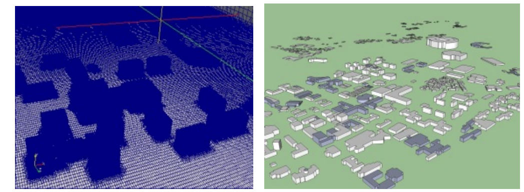
VirtualPULSE simulation platforms engineers interested in smaller scale modeling with open source/open access to the platform codes http://www.buildsci.us/efri-pulse.html

Research: Urban Modeling Platform

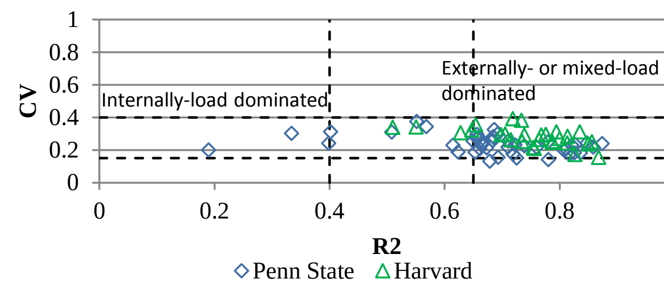


Research: Urban Modeling Platform

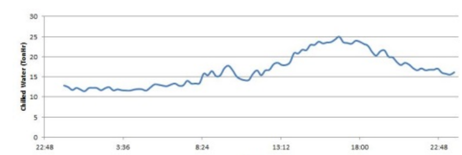
- Create EFRI PULSE database:
  - Urban models for the reviewed case studies.
  - Building classification based on energy use pattern into externally-load, internally-load, and mixed-load dominated buildings.
  - Templates for cooling, heating, and electricity schedules of the reviewed campus buildings.
  - Physical models based on the urban density (with case studies).
  - Comfort/Health outcomes for the reviewed case studies.



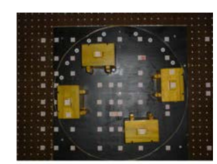
Penn State's campus: CFD model and SketchUP model



Heating season building energy use classification



An example of the chilled water schedule

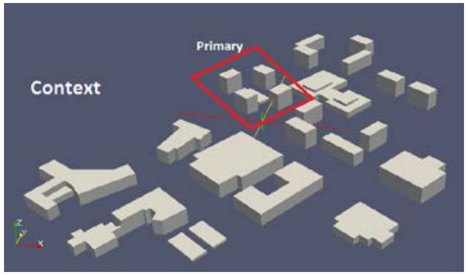


Wind tunnel model for East Halls buildings at Penn State

Research: Urban Modeling Platform

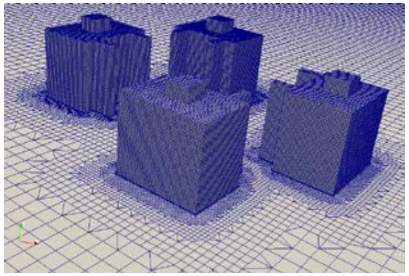
❖ Novelty of the platforms are associated to:

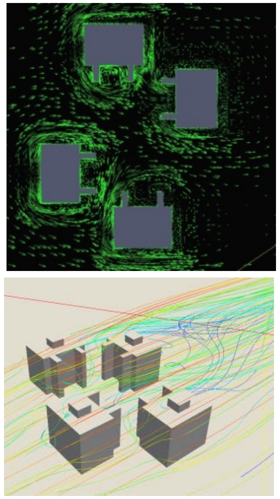
- Focus on different audiences.
- Enable online and offline simulations.
- Create an open source and open access platform.
- Rely on the developed physical models and databases for different urban densities.
- Integrate urban modeling through outdoor and indoor conditions while the focus is the human occupant.



(Primary & context buildings)

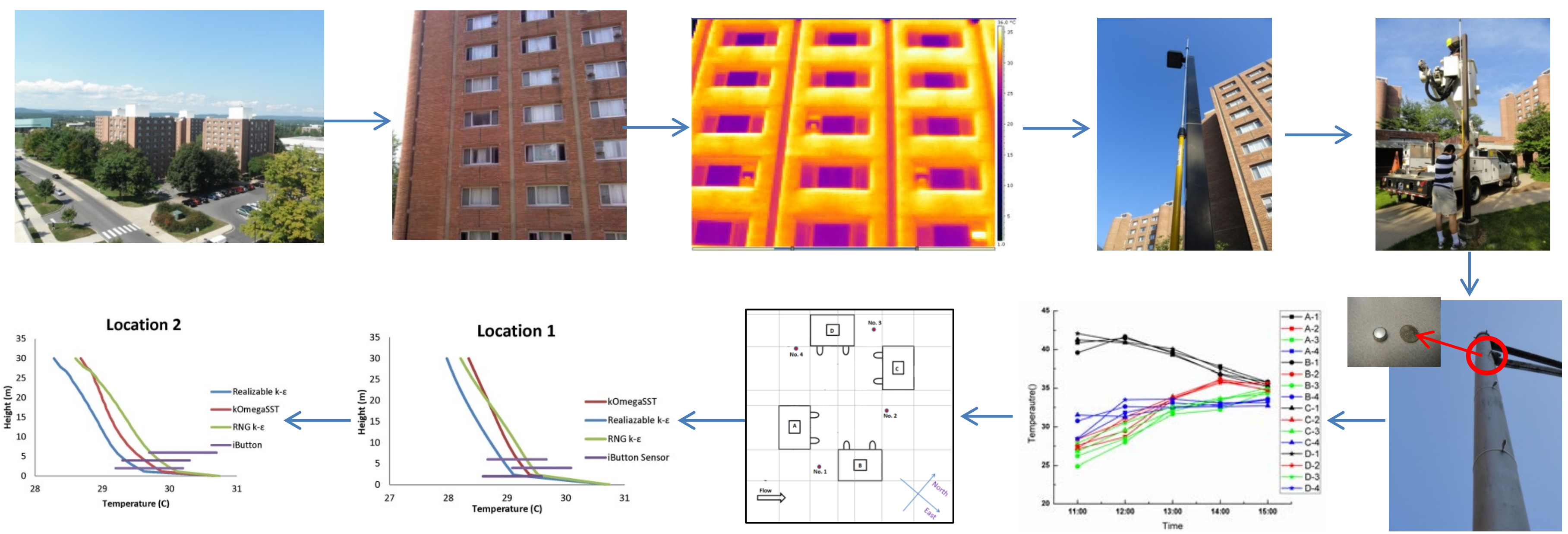

(Outdoor solar radiation)


(Automated mesh generation)


(CFD simulations)

Research: New Physical Models

- Develop new physical models for urban environment to reduce the complexity of the modeling:
  - **Outdoor Convective Heat Transfer Coefficients (CHTCs)**
  - **Outdoor Zero-Equation (ZEQ) Turbulence Models**



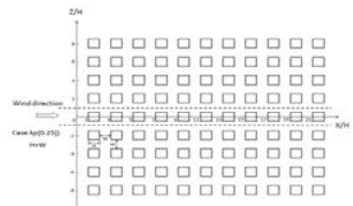
From outdoor field measurements to development of physical models

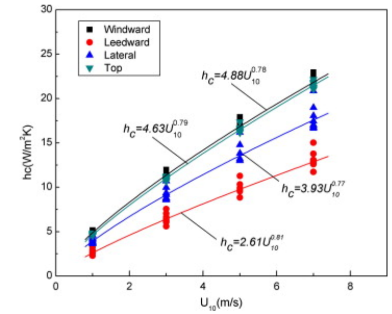
Research: New Physical Models

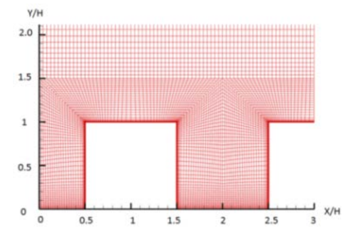
- **CHTCs**

❖ Hypothesis: Accurate calculation of the heat losses/gains through the building surfaces.

❖ Method: Using Large Eddy Simulation (LES) and validation of the results with wind tunnel measurements for different urban densities: 0.25m 0.16, 0.11, 0.063, and 0.04.





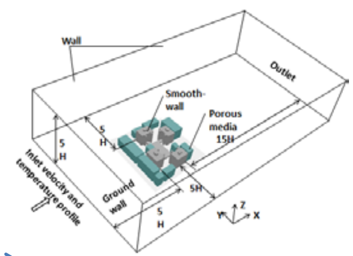


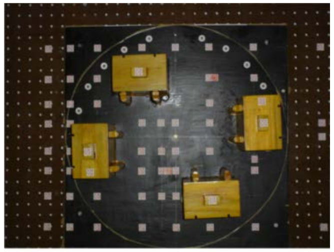
Surface	h_c for arrays of buildings $(0.04 \le \lambda_p \le 0.25)$
Windward	$(4.45 + 2.42\lambda_p)U_{10}^{0.78}$ (R^2=0.91)
Leeward	$(2.36 + 1.71\lambda_p)U_{10}^{0.79}$ (R^2=0.90)
Lateral	$(4.39 - 3.33\lambda_p)U_{10}^{0.78}$ (R^2=0.88)
Top	$(4.32 + 1.86\lambda_p)U_{10}^{0.79}$ (R^2=0.90)

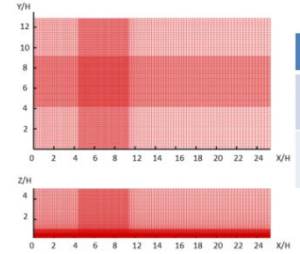
- **ZEQ:**

❖ Hypothesis: Rapid and reliable prediction of a real outdoor thermal environment in an urban area.

❖ Method: Integrate ZEQ model and CHTC wall boundary condition as well as validation with outdoor thermal environment measurement in the campus.

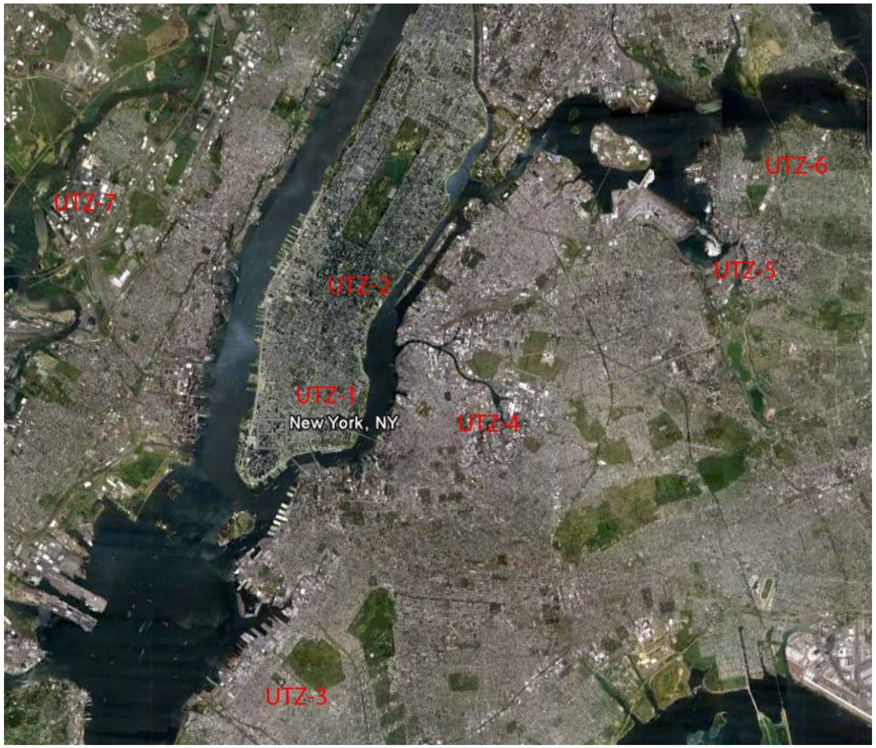






ZEQ Model	Height
$\mu_t = (3.15 z_h)\cdot\exp\left(-1.75\cdot \frac{L}{H}\right)\cdot\rho\cdot V\cdot\left(\frac{L}{H}\right)^2$	$z \le 1.3H$
$\mu_t = C_\mu k(z)^2/\varepsilon(z) = \frac{\kappa^2 U_H z}{\ln(z/z_0)}$	$z > 1.3H$

Research: New Physical Models



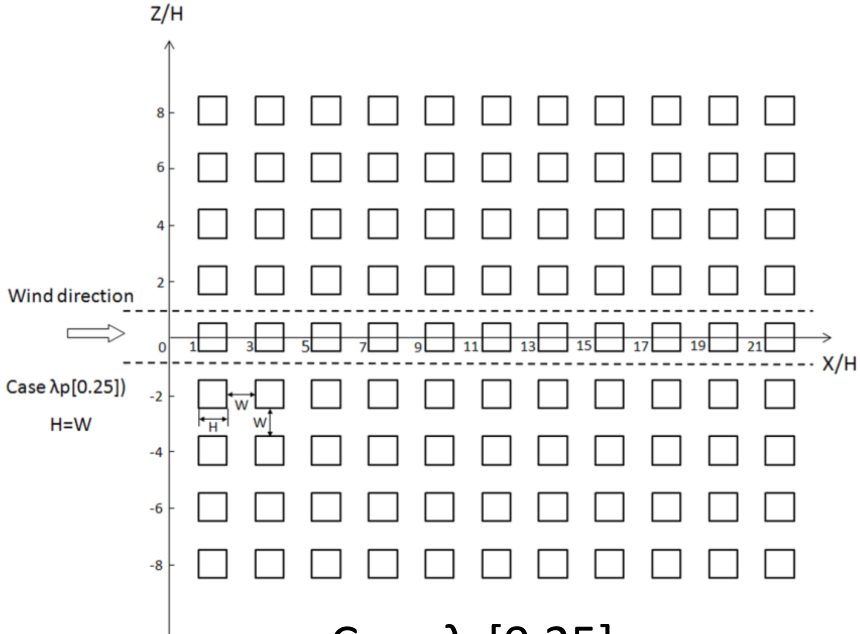
Zone	Urban Terrain Zone (UTZ)	Typical Location Within City
I	Attached and Closely Spaced Inner-City Buildings	City Core
II	Widely Spaced High-Rise Office Buildings	City Core and Edge of Built-Up City (e.g. near airports)
III	Attached Houses	Near City Core
IV	Closely Spaced Industrial/ Storage Buildings	Along Railroads Near Core and on Docks
V	Widely Spaced Apartment Buildings	Edge of city
VI	Detached Houses	Near Core and in Suburbs
VII	Widely Spaced Industrial/ Storage building	At City Edge Near Highways

Source: Ellefsen, 1999

Plan and Frontal Area Densities:

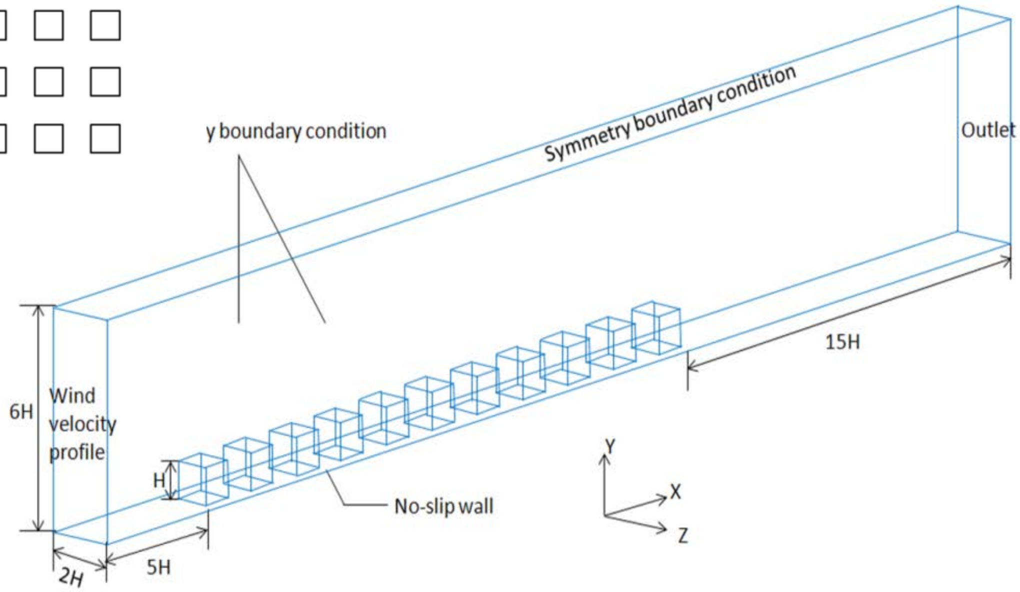
$$\lambda_p = \frac{\sum A_f}{A_{total}} \qquad \lambda_f = \frac{\sum A_w}{A_{total}}$$

Research: New Physical Models



Case λ_p[0.25]

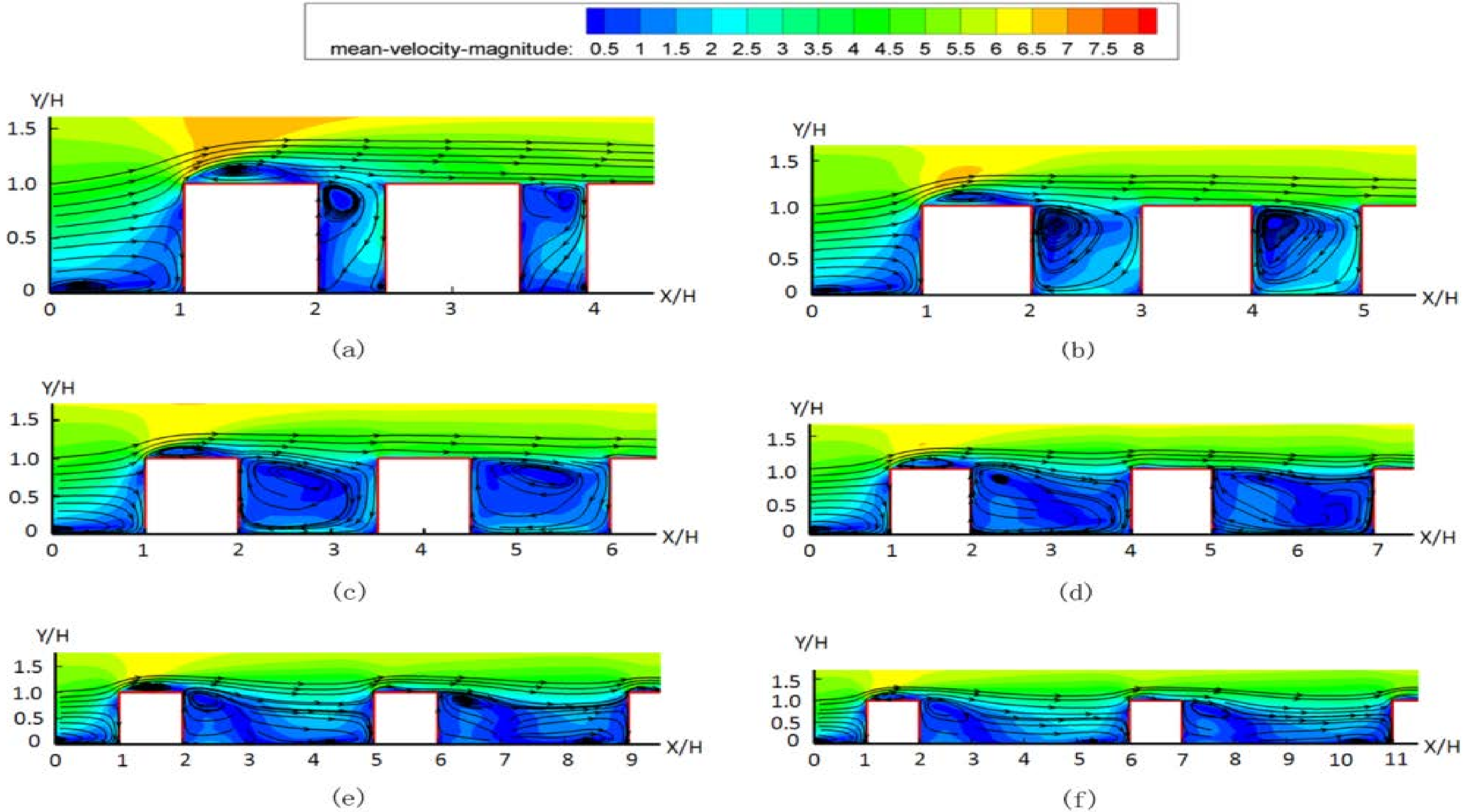
Standard wall functions can overpredict heat transfer coefficients on external building surfaces as much as 60% compared to low-Reynolds number turbulence models.



Simplified urban terrain studies are necessary to establish influencing parameters on transport phenomena

Research: New Physical Models

Mean velocity contours and streamlines through the first two rows of buildings



The plan area density affects both local air velocities and turbulence kinetic energy at the individual building surfaces

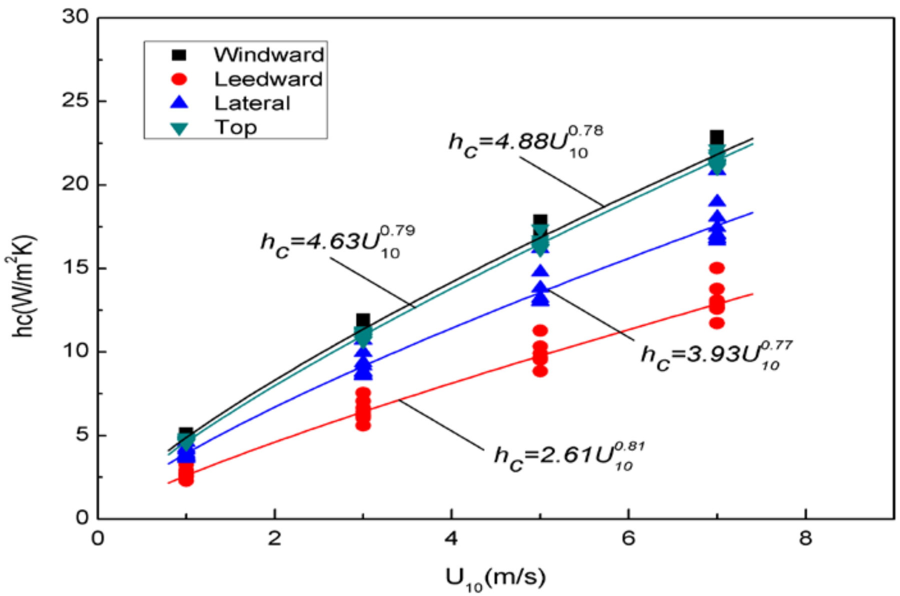
Research: New Physical Models

Surface	h_c for arrays of buildings ($0.04 \le \lambda_p \le 0.25$)	
Windward	$(4.45 + 2.42\lambda_p)U_{10}^{0.78}$	(R^2=0.91)
Leeward	$(2.36 + 1.71\lambda_p)U_{10}^{0.79}$	(R^2=0.90)
Lateral	$(4.39 - 3.33\lambda_p)U_{10}^{0.78}$	(R^2=0.88)
Rooftop	$(4.32 + 1.86\lambda_p)U_{10}^{0.79}$	(R^2=0.90)

Correlations:

$$h_c = aU_{10}^b$$

$$h_c = (a + b\lambda_p)U_{10}^c$$



For a constant incoming wind velocity U_{10}, with the increase of the plan area densities λ_p from 0.04 to 0.25, CHTCs increases 15% for the leeward surface and decreases 16% for the lateral surfaces

Research: New Physical Models

Turbulence viscosity expressions are scale dependent and even wind tunnel data are different from data collected in an actual urban environment

$$\mu_t = 0.03874\rho \cdot V \cdot L$$:Indoor environment

$$\mu_t = 0.2 \cdot \left(\frac{10^5}{\mathrm{Re}_b} \right) \cdot \rho \cdot T_{i\_\inf low} \cdot U \cdot L$$:Outdoor isolated building

$$\mu_t = \left(\frac{k_{in,H} \cdot \tau_{in,H}}{\nu} \right)^{1/3} \cdot L \cdot e^{-\left(\frac{U_{in,H} \cdot H}{\nu} \right)^{1/3} \cdot L} \cdot \rho \cdot V \cdot L$$:Outdoor multiple buildings

Application of zero-equation model to actual urban environment:

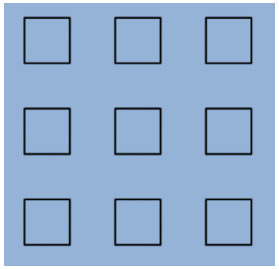
- ✓ The importance of building scale around urban environment
- ✓ Non-dimensional height (L/H)

Research: New Physical Models

Roughness height of surrounding terrain and morphological parameters of building terrain

$$\mu_t = (a \cdot z_h) \cdot \exp\left((1.5\lambda_p - 2.2) \cdot L/H\right) \cdot \rho \cdot V \left(L/H\right)^2 \quad z \le 1.3H$$

$$\left(0.1 \le \lambda_p \le 0.25\right)$$



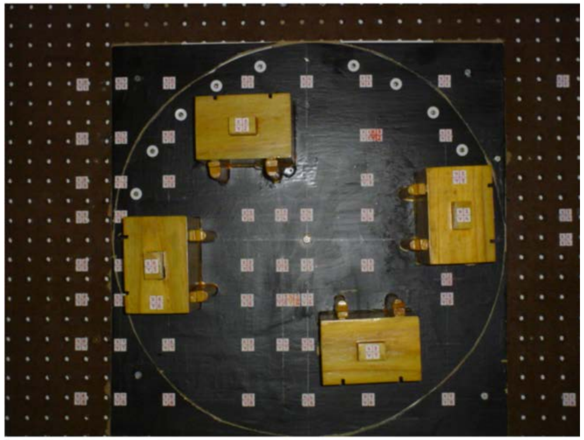
$$\mu_t = C_u k(z)^2 / \varepsilon(z) = \frac{\kappa^2 U_H z}{\ln(z/z_0)} \quad z > 1.3H$$

$$z_h = 0.1H \qquad a = (3 \sim 5)$$

$$\lambda_p = 0.25$$

$$z_h = 0.1H$$

$$\mu_t = (3.15 z_h) \cdot \exp\left(-1.75 L/H\right) \cdot \rho \cdot V \cdot \left(L/H\right)^2 \quad z \le 1.3H$$



$$\mu_t = C_u k(z)^2 / \varepsilon(z) = \frac{\kappa^2 U_H z}{\ln(z/z_0)} \quad z > 1.3H$$

The model calibration process requires measured data to establish value of the calibration coefficients in near and above building regions

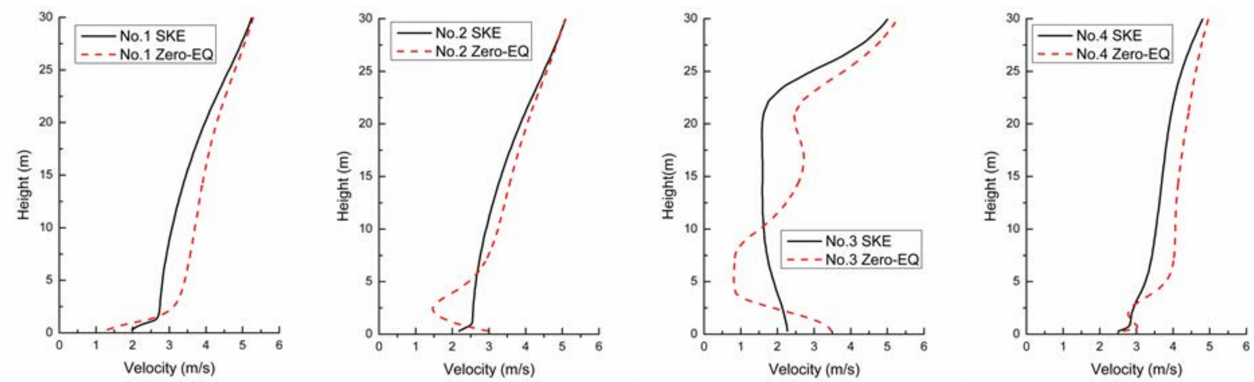
Research: New Physical Models

- The specific infrared camera measures temperature with <0.07°C thermal sensitivity and 2% accuracy.
- The temperatures of grass and concrete ground around these four student dorms were averaged.
- The approximate temperature range is 28°C - 44°C when directly exposed to the sun and 26°C - 38°C in the shade.
- The air temperature measurements use a wireless temperature system with accuracy of ±0.5°C from -10°C to +65°C and with the precision of 0.0625 °C.

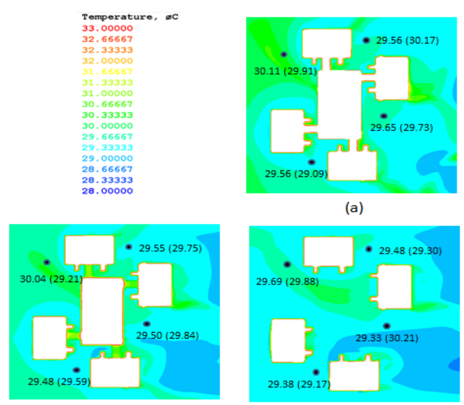
Research: New Physical Models

- Computational time: ZEQ:SKE = 1:1.8
- New ZEQ work faster and provide good agreement

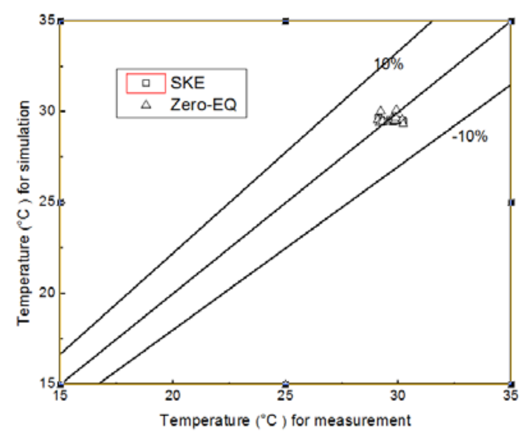
Velocity distribution:



Temperature distribution:



(a)
(b)
(c)



Overall comparisons between simulated by ZEQ, SKE and measured air temperature

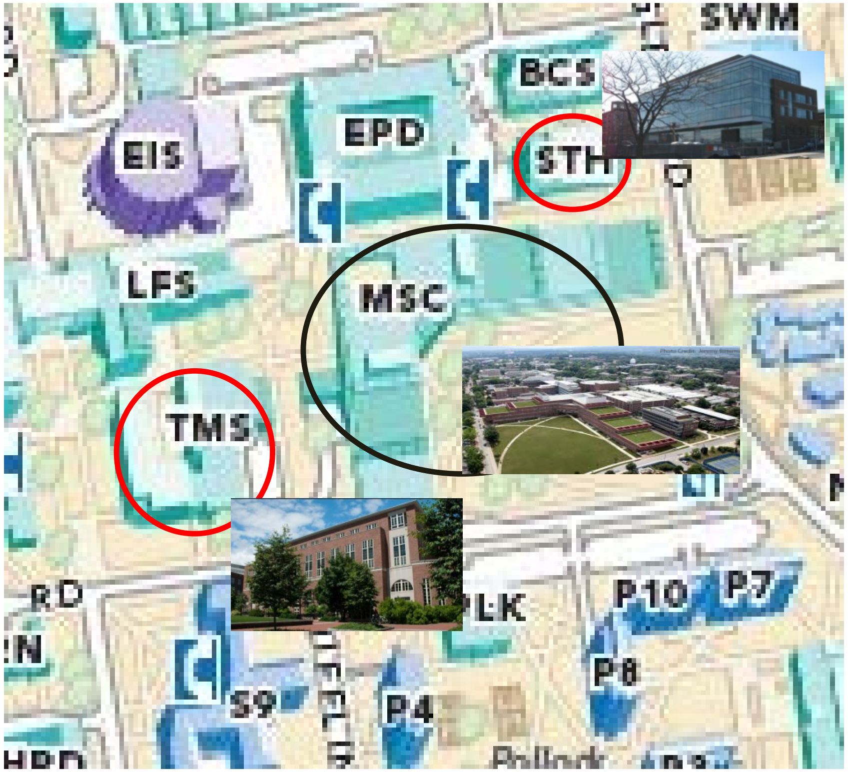
Research: Energy in Building Clusters

❖ Goal

- Evaluate building energy consumption before and after the change of neighborhood due to changes in urban environment.

❖ Method

- Statistical analysis of the energy consumption data normalized with CDD/HDD for 3 years and compare the regression results.
- Use suite of tools, E+ with CONTAMW, CFD0 to examine infiltration effects in different neighborhood context.



(MSC was added to the urban environment)

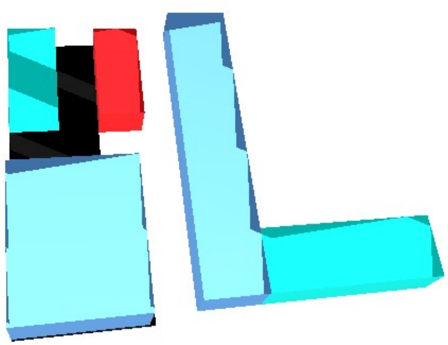
Research: Energy in Building Clusters

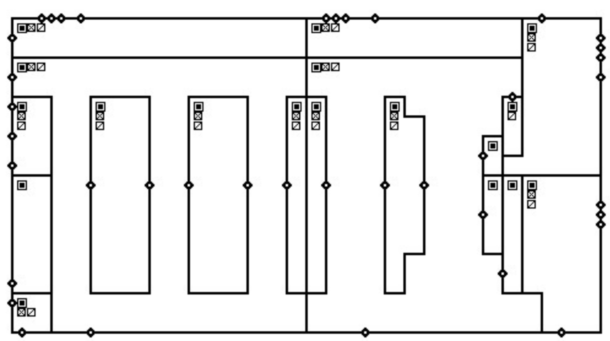
- Significant 2 sample T tests indicate different energy consumption patterns before and after the change of urban context.

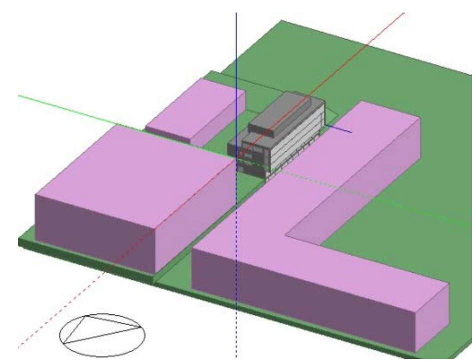
Energy type	R^2 adjusted	Significant relationship with CDD/HDD?	2010 Significant paired t-test?	2011: Significant paired t-test	Percentage of the energy use difference
TMS CHW	81	Yes	Yes	N/A	25%
TMS Steam	94	Yes	Yes	Yes	12%
STH CHW	68	Yes	Yes	Yes	46%

CHW = 3413478 + 469681×CDD (R^2 = 80.1% & P-value = 0.000)

- Integrate the outdoor air flow with infiltration and energy simulations.

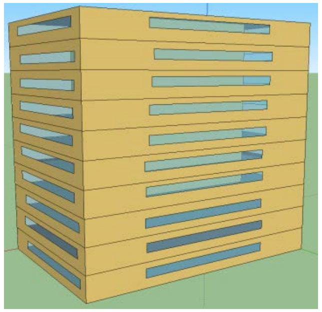




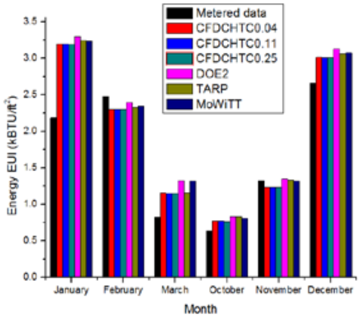


Coefficient of Pressure with Outdoor CFD → *Infiltration with CONTAMW* → *Energy simulation with context change*

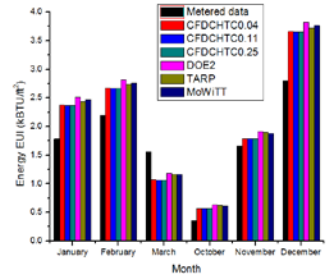
Research: Energy in Building Clusters



- Deploy the new developed CHTC models to energy models for buildings at Penn State.
- Results show that developed CHTC has:
  - Negligible effect on the total energy use of a building.
  - Significant influence on the outdoor properties such as surface temperature and COP of HVAC systems (up to 25%).



(a)



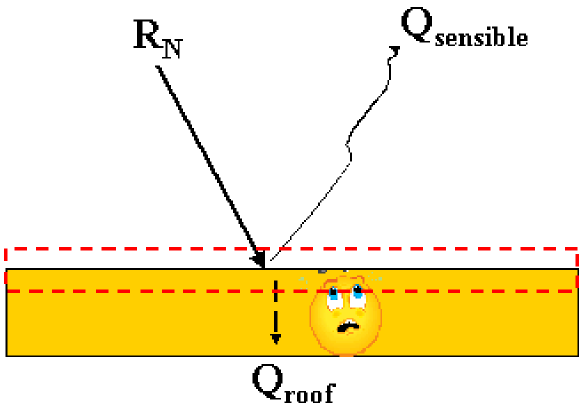
(b)

Monthly energy consumptions for space heating in (a) 2009 and (b) 2010.

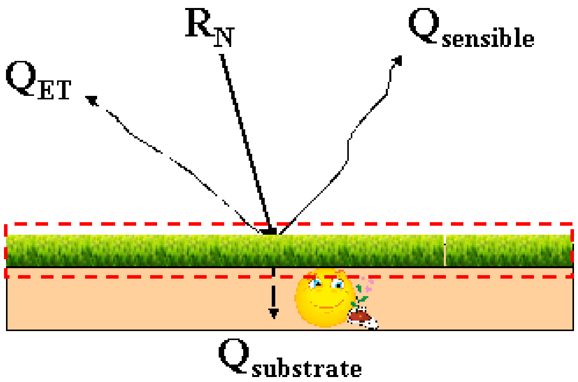
- Implementing urban environment based infiltration rate models to energy models (influence is up to 10%).

Research: New Physical Models

Traditional Roof



Green Roof



$$R_N - Q_{sensible} - Q_{roof} = 0$$

$$R_N - Q_{sensible} - Q_{ET} - Q_{substrate} = 0$$

Where,

R_N = net radiation

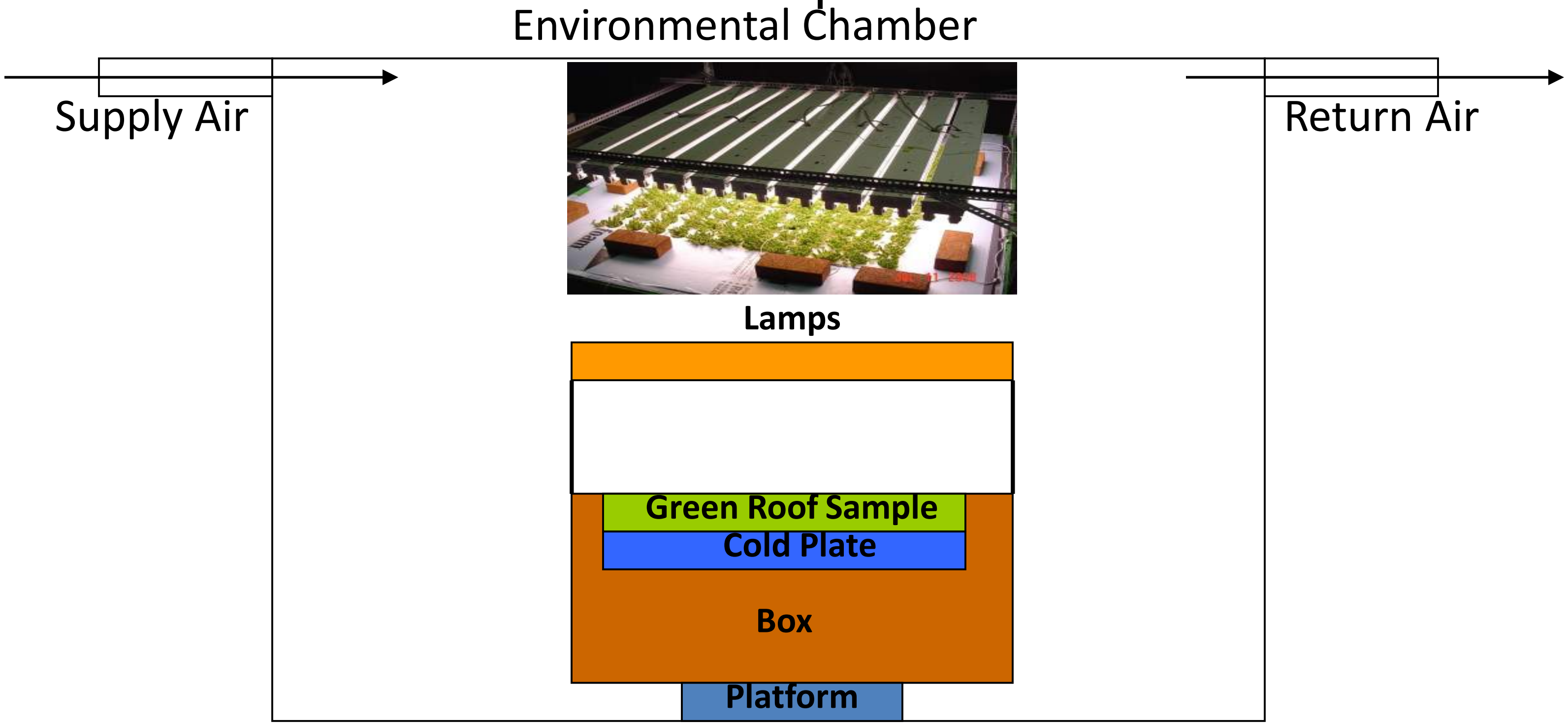
$Q_{sensible}$ = sensible heat flux due to convection

Q_{ET} = latent heat flux due to convection

$Q_{substrate/roof}$ = conductive heat flux through roof

Research: New Physical Models

- Inspired by ASTM C177 “hot plate” and C1363 “hot box”
- The design and construction was challenging
- Requires an environmental chamber
- Uses chamber and a bank of lamps as heat sources



Research: New Physical Models

Research: New Physical Models

- Green roof plants/substrates impact on roof thermal performance
  - 7 plant species
  - 5 substrate types
  - Same substrate thickness (3’’), LAI (2.5), plant coverage (0.75)
  - Insulated roof (R-15)
- combination of plants and substrates with the highest / lowest reflectivity

Case	Plants (albedo)	Substrates(albedo)
1	*Sedum tomentosum* (0.23)	Rooflite media (0.13)
2	Mixed species (0.11)	Rooflite media (0.13)
3	*Sedum tomentosum* (0.23)	Norlite (0.08)

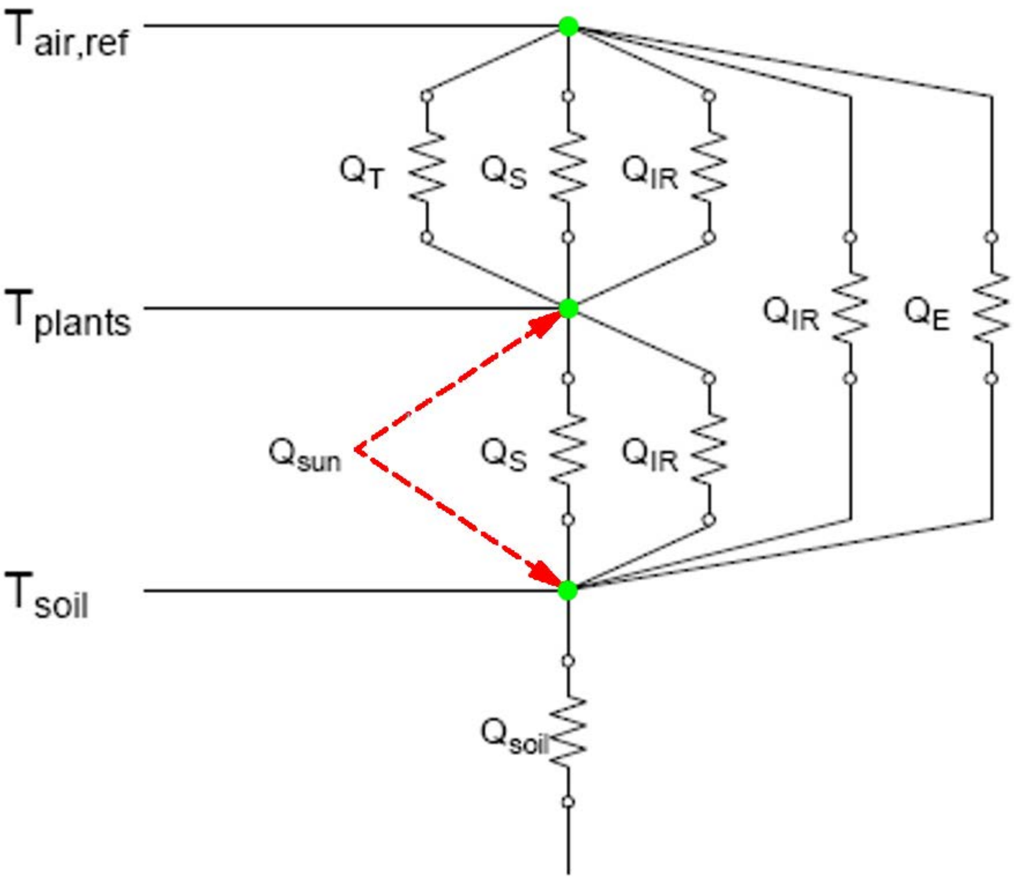
Research: New Physical Models

Latent heat flux for plants and substrate

Radiative heat flux:

- plants-sky
- plants-substrate
- sky-substrate

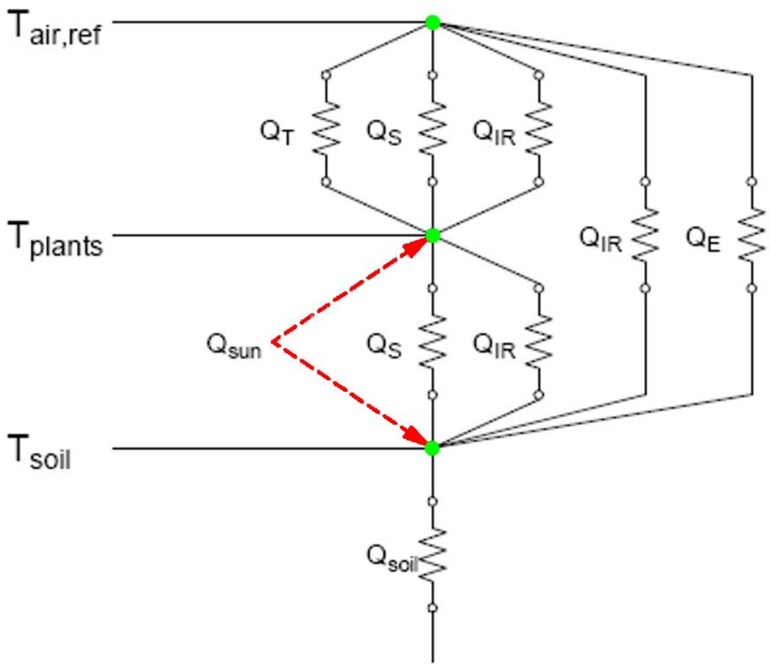
Complete heat transfer validation



Research: New Physical Models

- Roof without plants:

$$R_{sh,abs} = Q_{film} + Q_{conduction}$$



- Roof with plants:

$$R_{sh,abs} = Q_{film} + Q_i$$

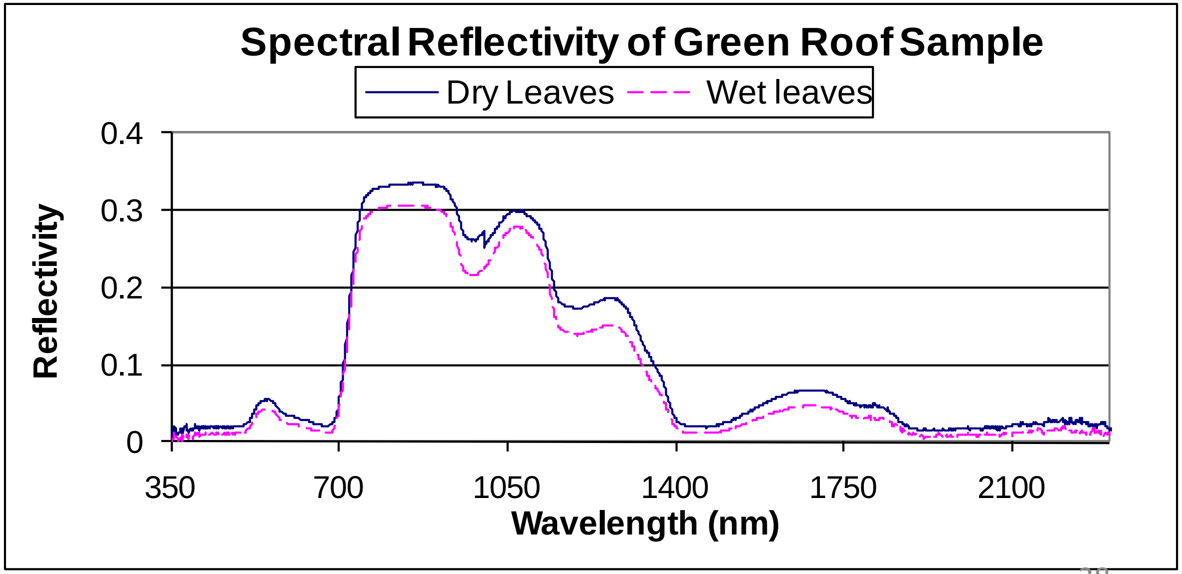
- Roof with plants: Substrate covered by plants

$$R_{sh,abs,cov,substrtae} + Q_i + Q_{substrate} - Q_{IR,sky,substrate,cov} - Q_{E,substrate,cov}$$

Research: New Physical Models

- Absorbed short-wave irradiance
- Thermal radiative heat transfer between:
  - Plants and sky
  - Plants and top substrate

$$R_n = Q_{solar}\left(I_{solar}, \rho_{soil}, \rho_{leaf}, \tau_{solar}, LAI\right) + Q_{IR}\left(T_{sky}, T_{soil}, T_{leaf}, \varepsilon_{soil}, \varepsilon_{leaf}, \tau_{IR}, LAI\right)$$



Research: New Physical Models

- Plants transpiration is controlled by stomatal resistance
  - Adjustable pores on leaves
  - Allow entry/release of gases for photosynthesis (CO2, O2 and water vapor)
  - Function of the LAI, solar radiation, temperature, and water availability

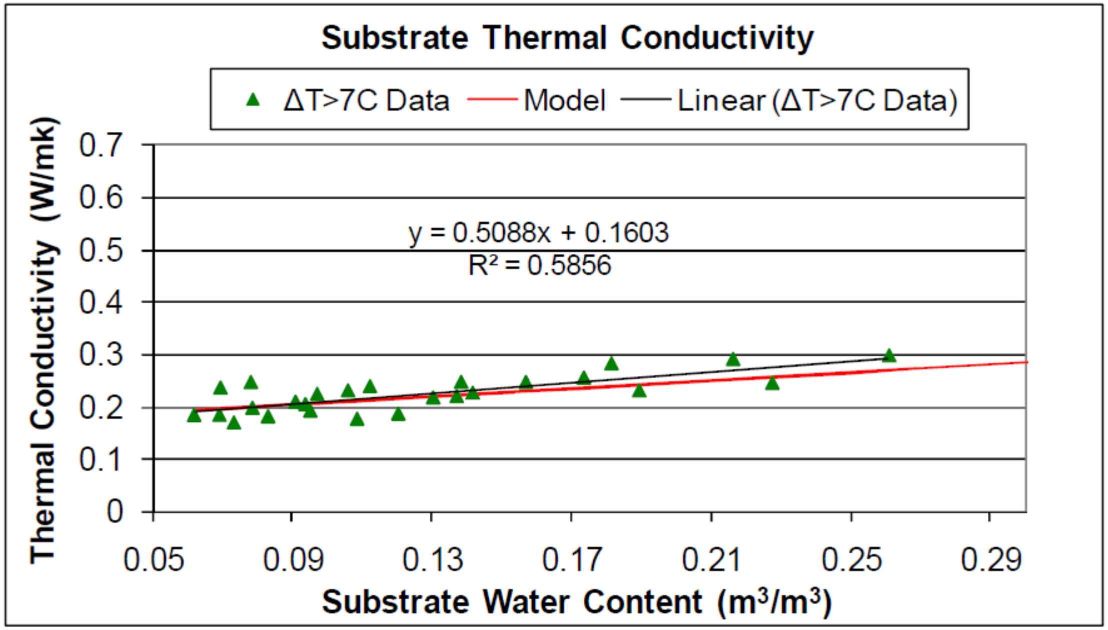
$$T = \frac{\rho C_p}{\gamma \left(r_{sto} + r_a \right)} \left(e_{so} - e_{air} \right)$$

$$r_{sto} = \frac{r_l}{LAI} f(solar) f(water) f(VPD) f(temp)$$

e_{so} = vapor pressure of the air in contact with the surface, kPa
r_{sto} = stomatal resistance to mass transfer, s/m
r_a = aerodynamic resistance to mass transfer, s/m
γ = psychrometric constant =
i_{fg} = enthalpy of vaporization, kJ/kg
P = atmospheric pressure, kPa

Research: New Physical Models

- Thermal conductivity depends on substrate type and water content
- Previous soil models overestimate thermal conductivity of green roof substrate
  - Substrate: 0.12-0.4 W/mK
  - Soils: 0.1-2 W/mK



Research: New Physical Models

$$R_n = Q_{ET} + Q_{sensible} + Q_{substrate}$$

$$Q_{ET} = \sigma_f \left(Q_{E,substrate,cov} + Q_{T,plants}\right) + \left(\mathbf{1} - \sigma_f\right) Q_{E,substrate,bare}$$

$$E = \frac{\rho C_p}{\gamma\left(r_{soil} + r_a\right)}\left(e_{soil} - e_{air}\right)$$

$$T = \frac{\rho C_p}{\gamma\left(r_{sto} + r_a\right)}\left(e_{so} - e_{air}\right)$$

Plus thermal mass effects…

$$Q_{sensible,plants} = \mathbf{1.5} \cdot LAI \cdot h_{conv}\left(T_{plants} - T_{air}\right)$$

$$Q_{sensible,substrate,cov} = h_{sub}\left(T_{substrate,top} - T_{air}\right)$$

$$Q_{substrate} = \sigma_f Q_{substrate,covered} + \left(1 - \sigma_f\right) Q_{substrate,bare}$$

$$Q_{substrate} = \frac{k_{substrate}\left(T_{substrate}^{top} - T_{substrate}^{bottom}\right)}{L_{substrate}}$$

Research: New Physical Models

- Total received **radiation** on the bare-soil substrate surface is ***32% (6.2 kWh m^{-2})*** larger than the total radiation received at the fully-coved green roof surface

- Total daily value of **latent heat fluxes** over the bare-soil roof is **negligible** compared to that value over the fully-covered green roof

- Daily peak value of the substrate surface temperature for the bare-soil roof is ***24°C (34%)*** higher than that over the fully-covered green roof

- In response to the change in plant coverage rate, ***the decrease in the annual cooling demand is significantly larger than the increase in the annual heating demand***.

Collaborations

- ❖ Dissemination of results to the OPP at Penn State
- ❖ Dissemination of results to the building industry through NREL's Building Component Library (BCL), a repository of building data to create building energy models.
  - Writing measures and components to create campus building templates based on the building classification results and CHTCs based on the new physical models.

Assessing the Role of Buildings in Sustainable Urban Eco-Systems

Questions?