A NEW PARAMETERIZATION FOR SURFACE HEAT FLUXES IN DENSE URBAN ENVIRONMENTS

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Outline

- Overview of the Energy Balance in Urban Environments
- Science Questions
- Methodology
- Evaluation
- Results for Surface Heat Flux Partition
- Summary and Conclusions
• **Surface Energy Balance (SEB):**

  SEB of an urban area can be defined as (Oke, 1998):

  \[
  Q^* + Q_F = Q_H + Q_E + \Delta Q_S
  \]
Energy Balance in Urban Environments

Water Balance

The water balance in urban areas is defined as (Oke, 1978):

\[ p + I + F = E + r + \Delta S \]

Weather Research and Forecasting Model (WRF)

Building Environment Parameterization (BEP)

Building Energy Model (BEM)

Surface Heat Flux Model (Hydro)

Latent Heat Flux Model from Buildings (CT)
Evaporation from engineered pavements and its cooling effect have long been ignored in most urban models (Nakayama and Fujita, 2010).

In highly urbanized areas, $Q_E$ is not negligible (Grimmond and Oke 1995; Grimmond et al. 2004; Christen and Vogt 2004; Moriwaky and Kanda 2004; Offerle et al. 2006a; Offerle et al. 2006b; Kotthaus and Grimmond 2014).

The omission of water is a main contributor to the inadequacy of current urban canopy models in predicting evaporation and latent heat budget (Grimmond et al., 2010).

Cooling loads from buildings are a main source of anthropogenic heat in summertime (Smith et al., 2009).

Cooling towers may have an important impact in the sensible/latent heat ratio (Sailor et al., 2007; Munck et. al 2013).
Specific science/engineering questions:

- **Major Questions:**
  - What may be the latent heat contribution to the total surface energy balance in dense urban environments?
  - What is the effect of anthropogenic heat (latent + sensible) production in the surface energy balance in urban environments during warm seasons?

- **Sub Questions:**
  - What may be the partition of anthropogenic latent/sensible heat in dense urban environments?
  - What may be the role of anthropogenic heat in summertime local climate and extreme weather heat events in complex urban environments?
  - What may be the role of anthropogenic heat in the initiation and evolution of the Planetary Boundary Layer in complex urban environments?
(a) Urban hydrology
(b) Building data assimilation
(c) Drag coefficients schemes.

Sectional drag coefficient (Default) = 0.4

Drag coefficient as a function of the building packing density (Santiago and Martilli 2010):

\[ C_{deq}(\lambda_p) = \begin{cases} 
3.32 \lambda_p^{0.47} & \text{for } \lambda_p \leq 0.29 \\
1.85 & \text{for } \lambda_p > 0.29 
\end{cases} \]

Average Building height PLUTO (over entire city) at 250 m (Right)

Hydrology Model for Impervious surfaces (to represent missing latent heat component) & improved mechanical surface representation.
Methodology-II
Cooling Tower Parameterization (to represent anthropogenic latent heat)

- **Effectiveness:**
  Ratio of the actual heat transfer to the maximum rate permitted by the second law of thermodynamics
  \[ \varepsilon = \frac{Q^*}{ma(h_{sai} - h_{ai})} \]

- **Energy Balance (Air):**
  \[ Q^* = m_a(h_{ao} - h_{ai}) - c_pT_{ao} + q_{vao}(c_{pw} + L) = h_{ai} + \varepsilon(h_{sai} - h_{ai}) \]

- **Condenser Heat Exchange:**
  Refrigerant R-134a (Typical Pressure: 160 psia, Saturation temperature: 43.3 °C, Superheated temperature (T_{Ref}) out of the compressor: 60 °C)
  \[ Q^* = c_{min}(T_{wo,cond} - T_{wi,cond}) \]
  \[ T_{wo,cond} = T_{wi,CT} \]
  \[ q_{max} = \frac{Q^*}{\varepsilon} = c_{min}(T_{Ref} - T_{wi,cond}) \]
  \[ T_{wi,cond} = T_{wo,CT} = T_{wb,air} \]
Methodology-III
Primary Land Use Tax Lot Output (PLUTO) Assimilation

PLUTO created by the Department of City Planning contains detailed tax lot building information for NYC.
## Ensemble Runs

<table>
<thead>
<tr>
<th>RUN</th>
<th>MODEL</th>
<th>PERIOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BEP+BEM _Cd_const</td>
<td>June 2010</td>
</tr>
<tr>
<td>2</td>
<td>BEP+BEM</td>
<td>June, July, August 2010</td>
</tr>
<tr>
<td>3</td>
<td>BEP+BEM + Hydro</td>
<td>June, July, August 2010</td>
</tr>
<tr>
<td>4</td>
<td>BEP+BEM + Hydro + CT</td>
<td>June, July, August 2010</td>
</tr>
<tr>
<td>5</td>
<td>BEP+BEM</td>
<td>July 2013</td>
</tr>
<tr>
<td>6</td>
<td>BEP+BEM + Hydro</td>
<td>July 2013</td>
</tr>
<tr>
<td>7</td>
<td>BEP+BEM + Hydro + CT</td>
<td>July 2013</td>
</tr>
</tbody>
</table>

**BB (Default BEP+BEM)**

**Hydro (BEP+BEM + Hydrology)**

**Hydro+CT (BEP+BEM + Hydrology + Cooling Tower)**
Three one-way nested domains with a grid spacing of 9, 3 and 1 km are defined. Initial and boundary conditions from NARR (resolution: 32 km). NCEP/MMAB data at 0.083 degree will update the sea surface temperature every 24-h.

Vertical resolution of 51 terrain following sigma levels (33 levels in the lowest 1.5 km, first level ~10m).

PBL Parameterization: BouLac (Bougeault-Lacarrere 1989)

Radiation Schemes: RRTM (Mlawer et al. 1997) and Dudhia (Dudhia 1989).

Microphysics: Single Moment 6-class (Hong et al. 2004).

Urban surfaces properties were adopted from Salamanca et al. (2014).

Building glass fraction and floor occupancy were obtained from the US-DOE (Deru et al. 2011).
NYC Evaluation
Datasets

- **Summer 2010:**
  - Hourly precipitation, temperature, wind and humidity data from 102 stations located at rooftops (NYCMetNet).
  - Stations with <10% of missing data were selected.

- **July 2013:**
  - 3-minute temperature and humidity data from NOAA-CREST and the Consortium for Climate Change Risk in the Urban Northeast (Vant-Hull et al. 2014)
  - Stations located at midtown and downtown Manhattan were used.
NYC Evaluation (Summer 2010)

Drag Coefficient

<table>
<thead>
<tr>
<th></th>
<th>RMSE</th>
<th>MAE</th>
<th>MAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cdrag</td>
<td>Cdeq</td>
<td>Cdrag</td>
</tr>
<tr>
<td>WS</td>
<td>2.78</td>
<td>2.48</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td></td>
<td></td>
<td>121.576</td>
</tr>
<tr>
<td>BK</td>
<td>2.06</td>
<td>1.434</td>
<td>70.48</td>
</tr>
<tr>
<td>QN</td>
<td>2.19</td>
<td>1.57</td>
<td>68.49</td>
</tr>
<tr>
<td>BX</td>
<td>2.21</td>
<td>1.39</td>
<td>109.71</td>
</tr>
<tr>
<td>MN</td>
<td>2.15</td>
<td>1.05</td>
<td>145.08</td>
</tr>
<tr>
<td>NJ</td>
<td>2.46</td>
<td>2.66</td>
<td>103.16</td>
</tr>
</tbody>
</table>

Average wind speed at the location of the weather stations for observations, Cdrag, and Cdeq simulations.
NYC Evaluation
Temperature NARR vs BEP+BEM

Observed and Modeled Temperature Daily Cycle (Summer 2010).

Observed and Modeled Temperature Daily Cycle (July 2013).
NYC Evaluation (Summer 2013)
Temperature and Humidity

Observed and Modeled (BEP+BEM and Hydro)
Temperature Daily Cycle for Dry Days.

Observed and Modeled (BEP+BEM and Hydro)
Specific Humidity Daily Cycle for Dry Days.

Observed and Modeled (BEP+BEM and Hydro)
Temperature Daily Cycle for Wet Days.

Observed and Modeled (BEP+BEM and Hydro)
Specific Humidity Daily Cycle for Wet Days.
Heat Partition (Summer 2010)

Modeled Latent Heat Daily Cycle for Residential (Left) and Commercial (Right) Areas.

Hourly Bowen Ratio at Midtown Manhattan.
Heat Partition (Summer 2010)
Spatial Distribution

Wet (1) and Dry (2) Days Average Daytime Sensible Heat Flux for Hydro(a), and Hydro+CT (b)
Heat Partition (Summer 2010)

Spatial Distribution

Wet Days Average Daytime Latent Heat Flux for BEP+BEM (a), Hydro(b), and Hydro+CT (c)
Anthropogenic Heat Partition (Summer 2010)
Daily Cycles


Anthropogenic Heat Partition (Summer 2010)
Spatial Distribution

Wet Days Average Daytime Latent Heat Flux for BEP+BEM (a), Hydro(b), and Hydro+CT (c)

Dry Days Average Daytime A/C Sensible (1) and Latent (2) Heat Flux (W/m2) for Hydro(a), and Hydro+CT (b)
Impacts on Local Climate due to Cooling Towers

Average Cooling Towers $\Delta T = -1.2 \, ^\circ C$

Hourly 2m Temperature Difference between Hydro+CT and Hydro.

Average Cooling Towers $\Delta RH = 4.4\%$

Hourly 2m Relative Humidity Difference between Hydro+CT and Hydro.
Planetary Boundary Layer
Vertical Profiles

Potential Temperature at 0600 LST for Commercial Areas.

Temperature (°K)

BB_WET
Hydro_WET
Hydro+CT_WET
BB_DRY
Hydro_DRY
Hydro+CT_DRY

MAGL

Temperature (°K)

Potential Temperature at 0600 LST for Commercial Areas during Extreme Events.

TKE at 1500 LST for Commercial Areas.

TKE (m²/s²)

BB_WET
Hydro_WET
Hydro+CT_WET
BB_DRY
Hydro_DRY
Hydro+CT_DRY

MAGL

TKE at 1500 LST for Commercial Areas during Extreme Events.
The new formulations properly represent sensible/latent heat daily cycles including anthropogenic heat partition for land use category (see next table).

The hydrology scheme improves air moisture content prediction particularly during rainy periods.

During wet days evaporation from impervious surfaces is the main source of latent heat in commercial areas.

Evaporative cooling technology from the air conditioning devices diminishes between 80 and 90% the amount of anthropogenic sensible heat with impacts in the local meteorology and urban climate.

Cooling towers reduce the unstable conditions in the lower troposphere during wet days while inducing neutral stability from the surface in dry days.

Future works will focus on further model validation (i.e. heat fluxes), scalability to regional scales (see posters by Ortiz et al. & Wu et al.), and transferability to other major cities.
Summer/winter mean and maximum (in parenthesis) anthropogenic heat estimations (W/m²) for different cities in commercial and residential sites.

<table>
<thead>
<tr>
<th>City</th>
<th>Summer COM</th>
<th>Summer RES</th>
<th>Winter COM</th>
<th>Winter RES</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo, Japan</td>
<td>(908)</td>
<td></td>
<td>(1590)</td>
<td></td>
<td>Ichibose et al. 1999</td>
</tr>
<tr>
<td>San Francisco, US</td>
<td>40 (60)</td>
<td></td>
<td>45 (70)</td>
<td></td>
<td>Lu and Sailor 2004</td>
</tr>
<tr>
<td>Philadelphia, US</td>
<td>25 (50)</td>
<td></td>
<td>40 (70)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toulouse, France</td>
<td>25</td>
<td>5</td>
<td>100</td>
<td>20</td>
<td>Pingeon et al. 2007</td>
</tr>
<tr>
<td>Tokyo, Japan</td>
<td>40 (86)</td>
<td></td>
<td>(18)</td>
<td></td>
<td>Moriwaki et al. 2008</td>
</tr>
<tr>
<td>Osaka, Japan</td>
<td>93 (161)</td>
<td>55 (60)</td>
<td></td>
<td></td>
<td>Narumi et al. 2009</td>
</tr>
<tr>
<td>Seoul, S.Korea</td>
<td>52 (65)</td>
<td></td>
<td>57 (75)</td>
<td></td>
<td>Lee et al. 2009</td>
</tr>
<tr>
<td>Incheon, S.Korea</td>
<td>50 (59)</td>
<td></td>
<td>56 (70)</td>
<td></td>
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</tr>
<tr>
<td>Gyeonggi, S.Korea</td>
<td>26 (30)</td>
<td></td>
<td>28 (35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sao Paulo, Brazil</td>
<td>11 (20.1)</td>
<td></td>
<td>13 (20.3)</td>
<td></td>
<td>Ferreira et al. 2011</td>
</tr>
<tr>
<td>Singapore</td>
<td></td>
<td></td>
<td>84 (120)</td>
<td>13 (15)</td>
<td>Quah and Roth 2012</td>
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<tr>
<td>Houston, US</td>
<td>14.6 (144)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>New York, US</td>
<td>23.5 (137.4)</td>
<td></td>
<td></td>
<td></td>
<td>Lee et al. 2014</td>
</tr>
<tr>
<td>Chicago, US</td>
<td>26.3 (83.1)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Los Angeles, US</td>
<td>23.9 (114.5)</td>
<td></td>
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<td></td>
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<tr>
<td>New York, US</td>
<td>64 (126)</td>
<td>13 (31)</td>
<td></td>
<td></td>
<td>Present study</td>
</tr>
</tbody>
</table>
The Holistic UBL
Methodology
Hydrology Model for Impervious and Natural Surfaces
Operational uWRF for NYC

- WRF-BEP/BEM daily real-time 72h simulations for NYC.
- Surface temperature, winds, hourly accumulated rainfall and energy consumptions products are available everyday at 9:00 AM.
- An automated evaluation system has been implemented and will be further improved

http://air.ccny.cuny.edu/ws/wrfn/thindex.wrfmetnet.php?initial=1