Validation of modeled anthropogenic heat fluxes using long-term energy-balance measurements

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Anthropogenic heat flux

• Anthropogenic heat is sensible and latent heat released by human activities. It can be a substantial term in the surface energy balance of an urban ecosystem.

• The anthropogenic heat flux $Q_F$ (in W m$^{-2}$) is hence a relevant term to be modelled or prescribed in atmospheric models to properly predict temperatures, heat stress, dispersion of air pollutants etc.

• Many studies in various cities have quantified $Q_F$ and neighbourhoods, typically using either bottom-up modelling or top-down consumption statistics.
Urban energy balance equation

\[ Q^* + Q_F + Q_H + Q_E + \Delta Q_S + \Delta Q_P = 0 \]

**Transportation**

\[ Q_F = Q_{FV} + Q_{FB} + Q_{FH} \]

Modeled by:
- **bottom-up** transportation models
- **top-down** power consumption

**Industry and buildings**

Modelled by building energy models

**Human metabolism**

Modelled using population data

Terms:
- net all-wave radiation
- anthropogenic heat flux
- sensible heat flux
- latent heat flux
- storage heat flux
- photosynthesis and respiration energy flux
A GIS-based bottom-up approach

**SUBMODELS**
- **Buildings**
  - LIDAR-informed building energy models for a small set of typologies quantify heat emissions in a bottom-up approach.
- **Human metabolism**
  - Calculated based on population downscaling (included in building energy models)
- **Transport**
  - Top-down modelling of traffic emissions based on splitting-up traffic counts and trip-diaries.

**MODEL OUTPUTS**
- **Q_{FB}**
  - Map of building emissions
- **Q_{FH}**
  - Map of metabolism emissions
- **Q_{FV}**
  - Map of traffic emissions
- **Q_{F}**
  - Summation of Components
  - Map of all emissions
  - Flux tower data
  - Independent, direct measurement of full energy balance (3+ years)

**MODEL COMPARISON**
Map of modelled building emissions $Q_{FB}$

Bottom-up modelling using 16 building archetypes in a building energy model.
Map of modelled transportation emissions $Q_{FV}$

- Modelling based on traffic counts and trip diary data.
- Separately accounting for latent and sensible heat emissions.

Knight / 49th Ave. seen from flux tower 78 W m$^{-2}$
Map of modelled human metabolism emissions $Q_{FH}$

Estimation based on downscaled night-time population density (census)

50 x 50 m raster of population density, land-use and LiDAR volume
Combined raster $Q_F$ (Total)

Entire study area

Average: 12.8 W m$^{-2}$
Maximum: 86.6 W m$^{-2}$
Modelled anthropogenic heat flux profile

- **12.8 W m$^{-2}$**
  - **4.3** sensible
  - **0.4** latent
  - **0.3** latent
  - **6.9** sensible

- **4.7 W m$^{-2}$**
  - **Vehicles**

- **0.4 W m$^{-2}$**
  - **Buildings**

- **0.3 W m$^{-2}$**
  - **Human metabolism**

All values in W m$^{-2}$

Entire study area
Annual variation of modelled $Q_F$

<table>
<thead>
<tr>
<th>Month</th>
<th>Buildings (W m$^{-2}$)</th>
<th>Transportation (W m$^{-2}$)</th>
<th>Human metabolism (W m$^{-2}$)</th>
</tr>
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<tbody>
<tr>
<td>Jan</td>
<td>19.2</td>
<td>5.0</td>
<td>2.0</td>
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<tr>
<td>Feb</td>
<td>17.5</td>
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<td>Mar</td>
<td>15.6</td>
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<tr>
<td>Jun</td>
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<tr>
<td>Jul</td>
<td>8.5</td>
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<td>Aug</td>
<td>8.5</td>
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<tr>
<td>Dec</td>
<td>19.0</td>
<td>19.0</td>
<td>2.0</td>
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</tbody>
</table>

Buildings:
- latent
- sensible

Transportation:
- latent
- sensible

Human metabolism:
- latent
- sensible

UBC a place of mind
System to measure energy balance on top of 30 m Vancouver-Sunset Tower
The energy balance residual approach (EBRA)

\[ Q^* + Q_H + Q_E + \Delta Q_P + \Delta Q_S + Q_F = 0 \]

Measured by net radiometer
Measured by eddy covariance system
Modelled using photosynthesis and respiration model separately for lawn and trees (small!)
Residual

For longer periods (e.g. full year): \( \Delta Q_S = 0 \) and residual is \( Q_F \)
Challenges of the EBRA

• **Different source areas** (turbulent: varies with wind etc., radiometer: static) - requires ‘homogeneous’ urban surface.

• Smallest systematic **errors will add up** over entire year.

Radiometer intercomparison vs. Environment Canada standards. Statistical gap-filling.

Turbulent fluxes corrected for density effects (WPL) and sensor separation effects. Despiking and statistical gap-filling. Instruments intercompared over ideal terrain.
Energy balance measurements

Measured average 2008-2011

- QP
- QE
- QH
- Q^*
- Residual

MJ m^{-2} month^{-1}

Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec

Gain for surface
Loss for surface
Monthly comparison

Modelled $Q_F$ ($W \, m^{-2}$)

Residual term ($W \, m^{-2}$)

Urban fabric cools

Urban fabric warms

-5 0 5 10 15 20 25 30

-5 0 5 10 15 20 25 30

May  Jun-Sep  Apr  Mar  Feb  Nov  Dec
Annual energy balance

On annual scale no storage is possible

-90
-60
-30
0
30
60
90

May 08 - Apr 09
May 09 - Apr 10
May 10 - Apr 11

QP
QE
QH
Q*
Residual

W m²

must be Q_f
Comparison of annual totals

<table>
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<tr>
<th></th>
<th>Measured</th>
<th>Modelled</th>
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<tr>
<td></td>
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<td>Average year</td>
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<tr>
<td>May 2008-</td>
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<td>12.8</td>
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<td>April 2009</td>
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<td>May 2009-</td>
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<td>April 2010</td>
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<td>May 2010-</td>
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<tr>
<td>April 2011</td>
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\(Q_F\) (W m\(^{-2}\))
Summary

• In our study area, the annual anthropogenic heat flux $Q_F$ modelled by a detailed bottom-up approach agrees surprisingly well with the annual value determined using the EBRA with a fully calibrated EB system.

• The fact that the EBRA results in similar $Q_F$ values in three consecutive years suggests that the EBRA is a reliable method to validate $Q_F$ models.

• On monthly scales, however, storage effects inhibit a direct determination of $Q_F$ using the EBRA.