Improving Representation of Anthropogenic Heating in Atmospheric Models

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Outline

• What is anthropogenic heating ($Q_f$)?

• How does $Q_f$ impact urban climate?

• How do we represent/model $Q_f$?

• Can we improve how we treat $Q_f$?
What is anthropogenic heating?

- Waste heat emitted into the atmosphere as a result of human activities
- Energy use is a key driver, but not the same as $Q_f$
- Key contributors include vehicles, industry, and buildings
**Transportation Sector** (~30% of energy use)

- Heat emissions
  - Exhaust, engines, brakes, tires
  - Roughly 3000 kJ/km driven

- Moisture emissions
  - Fuel + Air $\rightarrow$ Heat + $\text{H}_2\text{O}$ + ...
  - 1 liter fuel $\sim$ 1 kg $\text{H}_2\text{O}$

- When and where?
  - Near surface on roadways
  - Weekday vs. weekend
  - Rush hours
  - Modest seasonal variability
Industry (~30% of energy use)

- Some key industries
  - Industrial chemicals, mining, cement, paper and pulp, manufacturing

- When and where?
  - Some cities have more industry and manufacturing, often concentrated
  - Somewhat uniform distribution in time
  - Some emissions from elevated stacks often near/upwind of urban centers
Buildings (~40% of energy use)

- Heat Rejection from buildings
  - Internal loads (energy use)
  - Environmental loads

- Evaporative cooling is common
  - For residential in some climates
  - For large commercial
  - Up to 80% as latent heat

- When & where?
  - Weekday vs. weekend
  - Day vs. night
  - Residential vs. commercial districts
Impact of $Q_f$ on Urban Climate

Emissions distributed vertically and horizontally
Effects should likely also be distributed

*Solar radiation*
*Long-wave radiation*
*Sensible heat*
*Evaporative cooling*
*Anthropogenic emissions*
*Thermal storage*
Measurements of Effects of Anthropogenic Heating (at ground level)


Representing Anthropogenic Heating

• Top-down Inventory Approaches
  – Assume energy use = sensible waste heat
  – State-level monthly or annual electricity and heating fuel consumption data
  – Nominal traffic profiles and monthly or annual vehicle travel data
  – Need to map to city/neighborhood and hourly scales

• Bottom-up Energy Modeling
  – Use GIS data to assess distribution, sizes, and types of buildings and roadways
  – Use transportation models to assess vehicle emissions
  – Use building energy models to assess building emissions
  – Account for emissions in large and small industry
Inventory Approach for Anthropogenic Heat

City-scale anthropogenic heating profiles for January
Updated City-Scale $Q_f$ Profiles for 60+ US Cities (non-dimensional)

Summer

Winter

Louisville, KY
Memphis, TN
Miami, FL
Milwaukee, WI
Minneapolis, MN
Nashville, TN
New Orleans, LA
New York, NY
Oakland, CA
Oklahoma City, OK
Omaha, NE
Philadelphia, PA
Phoenix, AZ
Pittsburgh, PA
Portland, OR
Raleigh, NC
Riverside, CA
Sacramento, CA
Salt Lake City, UT
San Antonio, TX
San Diego, CA
San Francisco, CA
San Jose, CA
Seattle, WA
St. Louis, MO
Stockton, CA
Tampa, FL
Toledo, OH
Tucson, AZ
Tulsa, OK
Washington, DC
Wichita, KS
A Bottom-up Approach Based on GIS Land Use Data

• Buildings:
  • Define & model prototypical buildings for a city
  • Assign $Q_f$ to taxlots based on building parameters

• Vehicles:
  • Use diurnal profiles for traffic with nominal vehicle usage data
  • Map vehicle emissions onto roadways

• Industry:
  • Use LULC data to identify industrial areas
  • Uniformly map energy use (24/7)
Total: Vehicle + Building + Industrial Energy Use

Ching et al., BAMS 2009
A Bottom-up Approach based on data from Vehicle and Industry Emissions

- US National Emission Inventory (NEI) at 4km
- Regress CO and NO$_x$ emissions against the bottom-up Q$_f$ data base ($R \sim 0.85$)
- Extended to US at 4km

Summer daily mean anthropogenic heat flux

Lee et al., Atmos. Env., 2014
Modeling suggests it is important to capture spatial variation in $Q_f$

Anthropogenic sensible heating portion of urban warming at 0600 local time for:

(a) CityQf – a single city-wide value of hourly Qf
(b) LUQf – anthropogenic heat based on dominant land use
(c) ParcelQf – anthropogenic heat based on bottom-up approach

$\Delta T = \text{Control simulation} - \text{simulation with } Q_f$  Contour lines spaced every 0.25 °C.
Sensible vs. latent partitioning is important!

Figure 10. Comparison of the UHI generated by the four air conditioning scenarios.
Anthropogenic Heat as implemented in the WRF Mesoscale Atmospheric Model

Urban Parameterizations in WRF:
- Based on small number of urban categories
- UCM (default profiles, up to user to update)
- BEP (no $Q_f$)
- BEP+BEM uses an energy balance building model, ignoring transportation
Commercial

Hi-density Residential

Low-density Residential
Conclusions and Suggestions

• Anthropogenic emissions can have non-trivial effects on urban climate
  – but past studies have focused on near-surface emissions and air temperatures and ignored moisture effects

• Representation of anthropogenic emissions in mesoscale models is still crude
  – Default profiles often used and emissions are usually not height-specific
  – Some urban parameterizations ignore emissions from vehicles and industry; most ignore anthropogenic moisture

• Future developments
  – Vehicles (NEI-like data resource)
  – Buildings (national simulation-based data resource)
  – Industry (county-level intensity data – can we do better?)

Thanks!  sailor@pdx.edu
Extra Slides
Components of $Q_f$
(averaged over 60 + cities)

35-50% of $Q_f$
Human Metabolism & Respiration

- Metabolic rates range from < 75 W resting to > 250 W when active (avg. ~ 80-100 W).
- Humans exhaust ~0.1 kg/h of moisture
- Metabolic $Q_f$ varies with population density
  - 0.1 to 3 W/m²
- Most metabolic $Q_f$ is inside buildings
Where (and when) is $Q_f$?
Modeling $Q_f$ Impacts:

- 0.5-1 °C in summer
- 2-3 °C in winter

Temperature increases associated with anthropogenic heating in the **summer** simulations.

Temperature increases associated with anthropogenic heating in the **winter** simulations.
Sources of $Q_f$

- Buildings (Res + Comm)
- Industry
- Transportation Sector
- Human Metabolism (mostly in buildings)

US End-Use Energy Consumption

EIA, 2011
**Transportation Sector**

(\sim 30\% of energy use)

**Fuel + Air \rightarrow Heat + H_2O + CO_2 + N_2**

**Heat emissions:**

DVT = “daily vehicle travel” distance

HVT (hourly vehicle travel distance) = DVT * hourly fraction

Heat of combustion \sim 45 \times 10^6 J kg^{-1}

EV \sim 3975 kJ/km (for 8.5 km/l or 20 mpg)

\sim 2650 kJ/km (for 13 km/l or 30 mpg)

Vehicular heat flux is given by:

\[ Q_{f,\text{vehicle}} = HVT(h) \cdot EV \]

**H_2O emissions:**

1 liter gasoline yields \sim 0.9 kg water vapor

1 liter diesel yields \sim 1.0 kg water vapor

\[ \dot{m}_{H_2O,\text{vehicle}} = \frac{1 \text{kg/liter}}{10 \text{km/liter}} \approx 100 \text{g/km} \]

**Sources:**

Combustion Science and Engineering - CRC Press

ORNL – Fuel Property Comparisons www.ornl.gov