Quantification of fossil fuel CO$_2$ emissions at the urban scale:

Results from the Indianapolis Flux Project (INFLUX)

Jocelyn Turnbull, National Isotope Centre, GNS Science, New Zealand and CIRES, University of Colorado, Boulder, USA

Maria Cambaliza, Colm Sweeney, Anna Karion, Tim Newberger, Doug Guenther, Pieter Tans, Natasha Miles, Scott Richardson, Thomas Lauvaux, Kenneth Davis, Paul Shepson, Kevin Gurney, Yang Song, Igor Razlivanov, Scott Lehman
Why measure urban fossil fuel CO$_2$ emissions?

Emissions are increasing in spite of the global economic slowdown

Need to verify reported bottom-up inventories and monitor emission reduction efforts

Urban areas account for ~75% of total emissions

Need objective, independent estimates of emissions

Reported global fossil fuel CO$_2$ emissions

CDIAC, 2011
Top-down method

1. Measured CO$_2$ff mixing ratios
2. Atmospheric transport model
3. Calculated CO$_2$ff emission flux
Top-down method

\[ \text{CO}_2\text{obs} = \text{CO}_2\text{bg} + \text{CO}_2\text{ff} + \text{CO}_2\text{bio} + \text{CO}_2\text{oce} \]

- Large and varying \( \text{CO}_2 \) background

- Signal is typically only a few ppm

- Large seasonal, synoptic, diurnal variability
- May be co-located with \( \text{CO}_2\text{ff} \)

INFLUX upwind tower measurements
Top-down method

1. Make local background measurements
2. Use $^{14}$C to quantify CO$_2$ff in flask samples
3. Identify correlate tracer co-emitted with CO$_2$ff
4. Empirically determine tracer:CO$_2$ff emission ratio
5. Use high resolution tracer measurements to obtain high resolution CO$_2$ff mixing ratios

Atmospheric transport model

Calculated CO$_2$ff emission flux
INFLUX: Indianapolis Flux Project

Develop and test techniques/approaches for measurement of urban-scale greenhouse gas emission fluxes and to quantify uncertainties.

Aircraft-based measurements

Tower-based measurements

Bottom-up inventories

Data analysis and modeling

FTS

Driving tours
Sampling Strategy

12 cell phone towers, 75-150m high
Continuous in situ CO$_2$/CH$_4$/CO
Mid-afternoon conditional flask sampling
~50 species measured:
CO$_2$, $^{14}$CO$_2$, CO, CH$_4$, SF$_6$
hydrocarbons, halocarbons

Aircraft flights ~ every 2 weeks
donwwind of city
Continuous in situ CO$_2$/CH$_4$
6-12 flask samples per flight
Determine fossil fuel CO₂ from $\Delta^{14}$CO₂

$\Delta^{14}$CO₂ is lower at Tower 2

$^{14}$C-free CO₂ff decreases

$\Delta^{14}$CO₂

Fossil fuel CO₂ enhanced at Tower 2

$\text{CO}_2_{ff} = \frac{\text{CO}_2_{obs}(\Delta_{obs} - \Delta_{bg})}{\Delta_{ff} - \Delta_{bg}} - \frac{\text{CO}_2_{ref}(\Delta_{r} - \Delta_{bg})}{\Delta_{ff} - \Delta_{bg}}$
Determine fossil fuel CO$_2$ from $\Delta^{14}$CO$_2$

For each flight, a sample taken outside the urban plume is used as background

Fossil fuel CO$_2$ is enhanced in urban plume
CO as a correlate CO$_2$ff tracer in Indianapolis

Variable CO:CO$_2$ff ratio, especially at towers
CO associated only with mobile CO$_2$ff source sectors
CO as a correlate CO$_2$ff tracer in Indianapolis

Variable CO:CO$_2$ff ratio, especially at towers

CO associated only with mobile CO$_2$ff source sectors

Hestia bottom-up data product, Gurney et al., 2012
Contributions to CO$_2$ enhancement

\[ \Delta \text{CO}_2 \text{obs} = \text{CO}_2 \text{bg} + \text{CO}_2 \text{ff} + \text{CO}_2 \text{bio} + \text{CO}_2 \text{ocean} \]

\[ \Delta \text{CO}_2 = \Delta \text{CO}_2 \text{ff} + \Delta \text{CO}_2 \text{bio} \]

\( \Delta \text{CO}_2 \) in winter can be entirely explained by \( \text{CO}_2 \text{ff} \) addition

No apparent biosphere (respiration/photosynthesis) contribution

<table>
<thead>
<tr>
<th>Date</th>
<th>Slope (ppm/ppm)</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towers Winter</td>
<td>1.1±0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>29 Apr 2011</td>
<td>1.1±0.1</td>
<td>0.8</td>
</tr>
<tr>
<td>1 Jun 2011</td>
<td>0.9±0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>12 Jul 2011</td>
<td>1.2±0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>18 Aug 2011</td>
<td>N/A</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Why is Indianapolis total \( \text{CO}_2 \) enhancement dominated by \( \text{CO}_2^{ff} \)?

Choice of background directly upwind of city isolates ONLY the urban influence.

Continental background has a strong respiration influence in winter, consistent with previous studies.

When local upwind background is used, \( \Delta \text{CO}_2 \approx \Delta \text{CO}_2^{ff} \).

When continental background is used, \( \Delta \text{CO}_2 \approx 2 \times \Delta \text{CO}_2^{ff} \).
Urban flux estimate using aircraft in situ CO\textsubscript{2} and mass balance approach

\[ F_c = \int_0^{z_f} \int_{-x}^{+x} \left( C_{ij} - \overline{C}_b \right) * U_{ij} \, dx \, dz \]

- CO\textsubscript{2}ff flux
- CO\textsubscript{2} enhancement over background
- wind speed

In situ CO\textsubscript{2} measurement

Kriged CO\textsubscript{2} surface

Cambaliza et al., in prep
Hestia bottom-up emission estimates for Indianapolis

Annual totals have been distributed to hourly resolution
Power plant emissions at native hourly resolution from stack monitor
Estimated diurnal, weekly and seasonal cycles for transport, residential, commercial sectors

Annual total = 3.9 MtC

Gurney et al., 2012
Comparison of flux estimates from atmospheric observations and bottom-up estimates

Top-down and bottom-up estimates agree quite well
Conclusions

$^{14}\text{C}$ provides a strong constraint on fossil fuel CO$_2$
Ancillary tracers can potentially be used to partition the CO$_2$ff source sectors

With appropriate choice of background site, we found that CO$_2$ enhancements over Indianapolis are entirely due to fossil fuel CO$_2$ during most of the year

In situ CO$_2$ measurements from aircraft were used to estimate the fossil fuel CO$_2$ flux
Initial data shows bottom-up and top-down methods agree quite well

Ongoing research

Inverse mesoscale modeling to determine flux from tower observations

10 additional towers will test network design

Quantify uncertainties in top-down flux calculation

CO$_2$ff source sector apportionment with multi-species measurements