INVERSE DISPERSION MODELLING FOR A QUICK SCAN SERVICE TO ASSESS FUGITIVE EMISSIONS FROM LANDFILLS

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Outline

Context
- CH$_4$ produced by landfills
- GHG MRV and mitigation

Inverse modeling approach
- Experimental site
- Measurement protocol
- Multi-sources back-plume approach
- AMIS adaptive Bayesian approach

Dual tracer method
- Methodology
- Measurement protocol
- Results

Conclusion

From Chidambarampadmavath et al. Renewable and Sustainable Energy Reviews Volume 71, May 2017, Pages 555-562

9-12 October 2017 Bologna, Italy
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1 kg of CH\textsubscript{4} has the same impact on global warming than releasing 28 kg of CO\textsubscript{2} on a 100 years scale (IPCC 2013).

CH\textsubscript{4}

- 14% of the world GHG emissions
- 8.6% of the European Union GHG emissions in 2010.
  - 595 MtCO\textsubscript{2}eq in 1990
  - 405 MtCO\textsubscript{2}eq. in 2010 (a reduction of more than 30%).
  - 49% Agriculture & 32% Waste


Landfills: >15% of the total emission of CH\textsubscript{4}
Need of a routine “quick scan” service

- GHG MRV
- Checking collect and countermeasure efficiency
- Optimizing the biogas collect and its valorisation

- METHANE: ~50%
- CO₂: 35%
- Other gases: 15%
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Domestic / urban waste landfill

Rural site - Flat natural terrain

- Old one closed (1974-2004)
- Active one from 2005
  - ~ 250,000 t/year
  - 30 ha x H=20m; 2.8 M m³ / 3.1 M t
- Biogas 4.5 M Nm³ collected
- 9.5 GWhₑ ~900 toe (tep) saved
Experimental set-up & data

- **CH₄ measurement (dt = 1s)**
  - Picarro analyser (G2203)
  - Cavity Ring Down Spectroscopy
  - PC + GPS
  - Power supply

- Meteorological ground station

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9-12 October 2017 Bologna, Italy
Base on linearity between sources and receptors and steady state assumption: \( n \) area sources, \( m \) receptors

\[
\begin{bmatrix}
A_{11} & \cdots & A_{1n} \\
\vdots & \ddots & \vdots \\
A_{m1} & \cdots & A_{mn}
\end{bmatrix}
\begin{bmatrix}
Q_1 \\
\vdots \\
Q_n
\end{bmatrix}
+ 
\begin{bmatrix}
B_1 \\
\vdots \\
B_m
\end{bmatrix}
= 
\begin{bmatrix}
C_1 \\
\vdots \\
C_m
\end{bmatrix}
\]

- \( A_{ij} \) is the atmospheric transfer coefficient from source \( i \) to measurement \( j \)
- \( Q_j \) is the emission rate of the source \( j \) from 1 to \( n \)
- \( C_i \) is the measured concentration at receptor \( i \) from 1 to \( m \)
- \( B_i \) is the background at receptor \( i \) from 1 to \( m \) => \( <B> \)

Finding \( Q_j \) required \( [A_{ij}] \) (pseudo)inversion

- Quick means \( n \) and \( m \) not to big
- \( [A_{ij}] \) well conditioned
The “Condition Number” of matrix $A$, $\kappa(A)$, is an indicator of how the error on concentration may be amplified when source rates are obtained.

$$\kappa(A) = \frac{M_{\text{max}}}{M_{\text{min}}} = \|A\|_M \cdot \|A^{-1}\|_M$$

- Considering Euclidian distance
  $$\|x\|_E = \sqrt{\sum_{1}^{N} x_i^2}$$

- How much the matrix $A(n,m)$ can stretch vectors?
  - $M_{\text{max}} = \max \left( \frac{\|Ax\|}{\|x\|} \right) = \|A\|_M \text{ Considering “max distance”}$

- How much the matrix $A$ can shrink vectors?
  - $M_{\text{min}} = \min \left( \frac{\|Ax\|}{\|x\|} \right) = \frac{1}{\|A^{-1}\|_M}$
We need to solve a system $AQ = C$

- $C$ is corrected from background
- $\|C\| \leq M_{\text{max}} \|Q\|$

$$A(Q + \delta Q) = C + \delta C \text{ or } A\delta Q = \delta C$$

- $\|\delta C\| \geq M_{\text{min}} \|\delta Q\|$

$$\|C\|.M_{\text{min}} \cdot \|\delta Q\| \leq M_{\text{max}} \|Q\| \|\delta C\|$$

$$\frac{\|\delta Q\|}{\|Q\|} \leq \kappa(A) \left( \frac{\|\delta C\|}{\|C\|} \right)$$

If is greater than $\sim 20$

⇒ We cannot separate the different sources

Source: Flesch et al. (2009)
Optimisation of pseudo-sensors (matrix C)

17 November 2016

5 December 2016

9-12 October 2017 Bologna, Italy
Matrix A is computed using back-plume stochastic lagrangian model (MSS in ARIA View Package)

- Horizontal grid resolution: 5 meters
- Domain dimension: 1 kilometer x 1 kilometers
- Number of vertical levels: 21
- Lowest / Highest vertical level: 3 / 600 meters
- Number of receptors: 27 (for the 17th November), 29 (for the 5th December)
- Number of sources: 4 (for the 17th November), 5 (for the 5th December)
- Computation of source-receptor matrix: Each 5 minutes
- Estimation of emission rates: Each 15 minutes
Results

17 November 2017

**Before mitigation actions**

The global emission for the site: 3.85 t/day

\[ \kappa(A) = 5.9 \]

5 December 2017

**After mitigation actions**

The global emission for the site: 2.92 t/day

\[ \kappa(A) = 9 \]
Find the minimum of a cost function

The *Adaptive Multiple Importance Sampling* (AMIS) algorithm is based on an sampling scheme, where a target distribution (namely the posterior distribution) is approximated by weighted samples from a proposition distribution

The “*Adaptive*” algorithm improves the standard importance sampling procedure by:

- Allowing the update of the proposal distribution, which can be chosen as a flexible combination of well-known kernels (e.g. a multivariate Gaussian mixture)
- Optimally recycling the importance weights at each iteration to fully exploit the full available information and accelerate the convergence

Current version of the software: a unique point source ➔ here 4 or 5 area sources!

The AMIS algorithm

Test of the software “as is” on the 17 Nov 2017

Particles sampled at iteration 1 out of 8

Particles sampled at iteration 2 out of 8

Particles sampled at iteration 3 out of 8

Particles sampled at iteration 4 out of 8

Particles sampled at iteration 5 out of 8

Particles sampled at iteration 6 out of 8

Particles sampled at iteration 7 out of 8

Particles sampled at iteration 8 out of 8
Surprise : good order of magnitude !
- Back-plume method : 3.85 tons/day
- AMIS method : 3.46 tons/day

What we should expect with a single source
- A virtual point source upwind
- If in the area source ➔ a large underestimation
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Experimental set

- Dual gas is acetylene C$_2$H$_2$
- A C$_2$H$_2$ bottle and suitable flowmeter
- Same mobile C$_2$H$_2$/CH$_4$ PICARRO (G2203) installed in car
- Additional measurements with G2201 Piacarro CDRS (carbon isotopes apportionment)

Principle

- Release a known gas (here C2H2) in the same place of the unknown emission (here CH4)
- \[ Q_{CH4} = Q_{C2H2} \frac{A_{CH4} M_{CH4}}{A_{C2H2} M_{C2H2}} \]
  - \( Q_{CH4} \) targeted emission
  - \( Q_{C2H2} \) is the known release of acetylene (flowmeter + the bottle is weighted before and after the release (kg/h))
  - \( \frac{A_{CH4}}{A_{C2H2}} \) ratio of area peaks for the two gases (Picarro measurements)
  - \( \frac{M_{CH4}}{M_{C2H2}} \) ratio of molar mass
13 Sept 2016 Preliminary survey (before any mitigation actions)

- Identifying pics and order of magnitude
- Optimization of the C2H2 release
- Optimization of ambient concentration measurement protocol

<table>
<thead>
<tr>
<th>Variable (unit)</th>
<th>Typical value (during measurement)</th>
<th>Range of value (min/max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>28</td>
<td>23/31</td>
</tr>
<tr>
<td>Air Pressure (hPa)</td>
<td>1011</td>
<td>1009/1013</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>5</td>
<td>2.7/12.1</td>
</tr>
<tr>
<td>Wind direction (degrees) (coming from the direction)</td>
<td>SE</td>
<td>ESE/SSE</td>
</tr>
<tr>
<td>Rain (mm/3h)</td>
<td>0</td>
<td>0/1.4</td>
</tr>
</tbody>
</table>
Dual tracer experiment

19 Sept 2016 Dual gas tracer release

<table>
<thead>
<tr>
<th>Variable (unit)</th>
<th>Typical value (during measurement)</th>
<th>Range of value (min/max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>20</td>
<td>15/20</td>
</tr>
<tr>
<td>Air Pressure (hPa)</td>
<td>1018</td>
<td>1018/1020</td>
</tr>
<tr>
<td>Wind speed (m/s)</td>
<td>5</td>
<td>3.1/6.7</td>
</tr>
<tr>
<td>Wind direction (degrees) (coming from the direction)</td>
<td>NNW</td>
<td>NNW/WNW</td>
</tr>
<tr>
<td>Rain (mm/3h)</td>
<td>0.2</td>
<td>0/0.3</td>
</tr>
</tbody>
</table>

Time series downwind (14 transects)

Results

<table>
<thead>
<tr>
<th>N° Pic</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions de CH4 (kg/j)</td>
<td>5533</td>
<td>6005</td>
<td>7823</td>
<td>6925</td>
<td>4375</td>
<td>5177</td>
<td>3314</td>
<td>5278</td>
<td>6688</td>
<td>5697</td>
<td>4528</td>
<td>3485</td>
<td>6920</td>
<td>7497</td>
</tr>
<tr>
<td>Moyenne (kg/j)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5813 ± 1318</td>
</tr>
</tbody>
</table>
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Application to a mitigation policy

<table>
<thead>
<tr>
<th>Units</th>
<th>Reverse Modelling (1)</th>
<th>Dual Tracer (2)</th>
<th>((1)- (2))/ (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Mitigation (dual tracer, no reverse modelling)</td>
<td>t CH₄ emitted/d</td>
<td>5.8</td>
<td>5.8 ± 1.3</td>
</tr>
<tr>
<td>After phase I (North west of site : biogas network improvement)</td>
<td>t CH₄ emitted/d</td>
<td>3.85</td>
<td>3.6 ± 1.3</td>
</tr>
<tr>
<td>After phase II (cover and biogas network improvement)</td>
<td>t CH₄ emitted/d</td>
<td>2.92</td>
<td>2 ± 0.5</td>
</tr>
</tbody>
</table>

On progress

- In 2017: installation of an additional cogeneration engine corresponding to the amount of CH4 recovered and it is working!
- Test on an other site in Netherland (with TNO)
Acknowledgments

To HARMO18 Organizers!
For your attention!

For Partners of the WASTE MITI 2 consortium

For Climate KIC Contribution