Regional atmospheric inversion of CO2 and other GHG fluxes using CHIMERE

Focus on: estimates of the European CO2 natural fluxes and of the CO2 anthropogenic emissions from Paris

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and other CarboEurope-IP, ICOS, Geocarbon, AIRPARIF, CO2-Megaparis, Carbocount-city, LOGOFLUX, BridGES… partners
The need for characterizing the spatial and temporal distribution of the carbon fluxes

Global estimates: CO2 anthropogenic emissions and natural sinks/sources for 2000-2009

- Local, frequent and sectorial information on C-fluxes supports climate plans (verification, strategies for mitigation)
- Understanding the processes underlying C-fluxes based on high resolution information ➔ ability to forecast their evolution / impact
Uncertainties in traditional inventories of Carbon fluxes

- Large uncertainties especially at high spatial, temporal & sectorial resolution
- Need for an objective / independent quantification
- The atmospheric inversion developed by the scientific community can be used to improve / verify the inventories

Emission inventory data for Paris – for different emission data sets

<table>
<thead>
<tr>
<th></th>
<th>EDGAR V4</th>
<th>IER 2005</th>
<th>AIRPARIF2005</th>
<th>AIRPARIF2008</th>
<th>Max – Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>0.1° x 0.1°</td>
<td>1min x 1min</td>
<td>1km x 1km</td>
<td>1km x 1km</td>
<td></td>
</tr>
<tr>
<td>Annual budget of Ile-de-France (TgC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>6.75</td>
<td>5.36</td>
<td>5.65</td>
<td>7.80</td>
<td>31%</td>
</tr>
<tr>
<td>Road</td>
<td>8.50</td>
<td>6.03</td>
<td>3.63</td>
<td>3.37</td>
<td>60%</td>
</tr>
<tr>
<td>Industry</td>
<td>5.19</td>
<td>4.61</td>
<td>3.02</td>
<td>3.09</td>
<td>42%</td>
</tr>
<tr>
<td>Total</td>
<td>24.65</td>
<td>16.39</td>
<td>12.34</td>
<td>14.26</td>
<td>50%</td>
</tr>
</tbody>
</table>
Long-live GHG atmospheric inversions

Prior GHG fluxes ("bottom-up" inventories) with uncertainties

Inverted GHG fluxes with uncertainties

Simulation of the GHG atmospheric transport

Transport proxy/models bearing "model errors"

Statistical inversion: optimal corrections that minimize the sum of misfits to the measurements & prior

Comparison to the measurements

GHG atmospheric measurements with measurement errors

- Need for high precision meas, transport model; chemistry often neglected
- Used for more than 10-years to estimate natural fluxes at global scale
- Emergence of regional systems: ability to derive more robust local estimates and to track anthropogenic emissions
CO2 Net Ecosystem Exchange (NEE) from global atmospheric inversions in Europe

*Inter-annual variations* (smoothing window=3 years)

*Mean seasonal cycle*

- CO2 atmospheric concentration in Europe relatively well sampled: CarboEurope-IP, ICOS continuous networks
- **Results from global inversions**
  - High uncertainty on inter-annual variability
  - Stronger consistency on the seasonal cycle
  - High uncertainties on the spatial variations
- Use of mesoscale / **regional inverse modeling** systems to refine the results

Source: Peylin et al. 2013, BG (RECAPP synthesis of natural fluxes from global inversions)
Regional inversion of CO2 NEE in Europe using CHIMERE

**Prior NEE:** ORCHIDEE

Uncertainty: ~1.5-2.5 gCm\(^{-2}\) day\(^{-1}\)
Corr len ~250 km/1 mth for a given 6-hour window

**Optimized fluxes and uncertainties**

**Adjoint of CHIMERE**

**CHIMERE-MM5/ECMWF**
Europe config
0.5° resolution
FF: EDGxEMEPxCDIAC
BC: GLOB INV-LMDZ

**Optimized fluxes and uncertainties**

**Corrections to NEE at 6-hour / 0.5° resolution**

**CarboEurope IP / ICOS**
hourly data
low alt.: 12:00-20:00
high alt.: 0:00-6:00
transport error: ~4-15 ppm

**Variational inverse modeling** with Monte Carlo estimates of uncertainties (Chevallier et al. 2007)

Broquet et al. 2011, JGR
Estimation of the model error

- **222Rn and CO2 at Heidelberg during summer 2007:**
  - **Data +/- CHIMERE transport error (STD)**
  - **Global inversion of Chevallier et al. 2010**
  - **CHIMERE: prior fluxes**
  - **CHIMERE: inv fluxes**

- **Sensitivity of CO2 to erroneous PBL height, topog., synoptic events** *Aulagnier, 2009, PhD*
- **Radon model-data comparisons** *Aulagnier et al., 2009, Tellus; Broquet et al. 2011, JGR*
  - Biases exist but cannot be accounted for by inversion
  - **Obs selected for assimilation** (low altitude: 12:00-20:00; mountains: 0:00-6:00)
Estimate of Uncertainty Reduction (UR) for NEE

- **UR = 1 - ( std uncert a posteriori / std uncert a priori )**
- UR for 1-month / West. Europe with existing network: ~60% throughout 2002-2007
- High UR estimated vs high prior uncertainty from a biosphere model (potential improvement of prior at low resolution using bottom-up inventories)

\[ UR = 1 - \frac{\text{std uncert a posteriori}}{\text{std uncert a priori}} \]

**UR for 30-day avg NEE for each 6-hour window of the day (summer 2006; use of CE-IP stations)**

**UR for 14-day avg NEE (July 2007; use of 50 ICOS near term stations)**

Broquet et al. 2011, JGR

Kadygrov et al. 2013, in prep
Inversion of CO2 NEE in Europe for 2002-2007: comparison to the eddy covariance flux data

Broquet et al. 2013, ACP

30-day avg NEE (gCm⁻²day⁻¹) at CE-IP eddy covariance flux measurement sites.

Shadded areas: +/- std of model uncertainty

Statistics on 30-day mean NEE at EC sites

<table>
<thead>
<tr>
<th></th>
<th>a priori</th>
<th>a posteriori</th>
<th>UR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS of the uncertainty STD</td>
<td>0.69 gCm⁻²d⁻¹</td>
<td>0.33 gCm⁻²d⁻¹</td>
<td>53%</td>
</tr>
<tr>
<td>STD of the misfits to EC data</td>
<td>0.64 gCm⁻²d⁻¹</td>
<td>0.4 gCm⁻²d⁻¹</td>
<td>38%</td>
</tr>
</tbody>
</table>

- Misfits to EC data include **repr error** and **eddy covariance meas errors**
- Fair consistency: high confidence in the results at European/monthly scale
Robustness of the estimate of the variability in Europe NEE: comparison variability vs the uncertainties from the inversion

Mean seasonal cycle (of 30-day avg NEE in gCm\(^{-2}\)day\(^{-1}\) over Europe

Shaded areas=+/− std of model uncertainty

Dotted lines=+/− std of the inter-annual variability

- Confidence in the estimate of uncertainties in NEE at Europe / monthly scale
  - The (correction to the) seasonal cycle from inversion is reliable
  - Difficulties to monitor the inter-annual variability ( < posterior uncertainties )
Atmospheric monitoring of city CO2 emissions

- Cities: more than 75% of GHG emissions on less than 2% of land surface
- Political need for improving / verifying the estimate of emissions from cities
- Increasing number of city scale in situ CO2 measurement networks:
  - difficulties to deal with local signals, to get integrated views of city plumes
  - political issues for setting-up in situ networks dedicated to verification
- Future satellite high res imagery of XCO2 (2 to 4-10 km / ~1 to 5 days)
  - Cannot monitor a city continuously
  - Issues: high meas errors, lower signal, linking fluxes to column integrated mixing ratios

- Study of the potential of in situ and satellite atmospheric data for quantifying city emissions using the Paris area
Inversion of CO2 emissions from Ile de France using ground based measurements: “ingredients”

• The AIRPARIF inventory with **good spatial distribution & annual mean** but assumptions of homogeneity for the temporal profiles

• Existing ground network = 1 site in Paris + 3 sites close to the urban core + 1 site outside IdF

• Transport model at 2km res with too much diffusion & not urban parameters presently (difficulties to model urban sites)

➤ **Objectives:** improving the inventory regarding the monthly IdF emissions and their temporal variations (daily resolution) without solving the spatial distribution

**Temporal variations of the CO2 emissions per main sector in the AIRPARIF inventory**

**CO2 surface flux in the CHIMERE configuration (gCm\(^{-2}\)d\(^{-1}\)) and the CO2-MEGAPARIS / ICOS sites**
Inversion framework

PRIOR FF: AIRPARIF (/ IER / EDGAR)
PRIOR NEE: C-TESSEL (/ ISBA)

Analytical inversion (transport matrix built with response functions to individual flux components)

CO2-MP / ICOS hourly gradients to ref site 12:00-16:00 when wind > 3ms\(^{-1}\) no urban site (EIF)
Grad to GIF when SW winds and grad to MON when NE winds

Uncertainty in FF: 20% in monthly fluxes Correl length ~1 week for a given 6-hour window

OPTIMIZED FLUXES and uncertainties

corrections to total NEE and FF in IdF at 6-hour resolution

Puygrenier et al. 2013, in prep
Bréon et al. 2013, in prep

Model error ~5 ppm
Results for Oct 21 – Nov 19 2010

12:00-16:00 mean gradients to GIF and MON at GON when the wind blows from SW and NE respectively

30-day budget of CO2 fluxes in the IDF “region” defined by the control vector FF NEE Total

- The data selection leaves relatively few data for assimilation but the system diagnoses some significant uncertainty reduction
- Need for validation data or longer experiments (to assess the agreement with indexes such as cold/warm events): on-going analysis of 1-year inversions
- The use of gradients requires a site upwind: limits the ability to monitor continuously the emissions (unless having a “ring” of station around the city)
Use of other data-streams to constrain the CO2 inversion

Analysis of CO/CO2 ratios at GIF and TRN

- Monitoring pollutants co-emitted with CO2 (CO, NOx...) and C-isotopes ($^{14}$C, $^{13}$C) helps constrain CO2 emissions, their separation from natural fluxes and their resolution by type of fuel (~sector), by sector and in space / time.

➤ Development of a multi data stream system for the city scale inversion (FFDAS) in collaboration with the air quality community.

Analysis from L. Wu
Evaluation of the potential of future satellite imagery for city scale inversions

- Inversions of 5-hour emissions using individual satellite images
- **Uncertainty could be increased by the assimilation of satellite data** due to source of biased & non-Gaussian errors

➤ high res sun-synchronous imagery could not be used to resolve city-scale fluxes with sufficient accuracy based on state of the art inversion methods

- For Carbonsat, only 20 cases of cloud free images of the plume per year
  ➤ Need for knowledge on temporal profiles to derive daily to annual FF

**An unfavourable case: “true” and “observed”**

XCO2 at 2km res. (11:00 on Oct 14th)

**A realistic distribution of cloud cover and systematic errors for Carbonsat**

*Source: IUPB*
Conclusions (1): some insights for the improvement of the results

- **Need for methodological improvement of inversions to fully exploit the data** (reject less in situ CO2 data, decrease the impact of model / measurement errors)
  - cannot overcome all issues due to model / measurement errors
  - but could lead to critical improvements as long as there is no breakthrough improvement of the models and measurement: relevance for the long term?
- The **complementarity with in situ data** seems critical for satellite data (at least due to the need for gap-filling)
- City scale inversion: **stronger links with air quality community**
- The concept of monitoring the city emissions based on ground based network is not “validated” yet but a stronger assessment of feasibility may require a larger number of stations
Conclusions (2): objectives

- Next targets
  - For the European CO2 flux inversion: use of satellite data; inversion of anthropogenic emissions
  - For the Paris scale CO2 flux inversion: use of urban meteorology, subgrid scale simulations (Carbocount-city), use of co-emitted species, C-isotopes, test of geostationary missions (chaire industrielle BridGES); attempt at increasing the spatial / sectorial resolution

- Other regional inversions of GHG fluxes at LSCE:
  - biogenic and anthropogenic CO2/CH4/N2O in Europe
  - biogenic and anthropogenic CO2/CH4/N2O in France (coupling with Europe)
  - biogenic CO2 in South America (coupling with CATT-BRAMS)
  - biogenic and anthropogenic CH4 in Siberia
  - CO2 City-scale inversions for London