The CO2 Human Emissions Project at ECMWF

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**Project aim:**

Design a European system to monitor human activity related carbon dioxide (CO2) emissions.

**With the following objectives:**

1. Detection of emitting hot spots e.g. megacities or power plants.
2. Assessing emission reductions/increase of hotspots.
3. Assessing emission changes against local reduction targets to monitor impacts of the NDCs.
4. Assessing the national emissions and changes in 5-year time steps to estimate the global stock take.

*Pinty et al., (EC CO2 report, 2017) Janssens-Maenhout et al. (BAMS, 2020)*
Global nature run: from inter-hemispheric gradient to plumes

XCO₂ enhancement [ppm] associated with emission sectors and biogenic fluxes during 1-day FC

XCO₂ Paris TCCON site (January)

[Diagrams showing maps and data analysis for different emission sectors (Energy, Residential, Transport, Biogenic) and background emissions, with color-coded representations for each category.]
CHE global nature run based on CAMS CO2 forecasting system

CO₂, CH₄, linCO₂, tagged tracers at Tco1279 (~9km) L137

- CTESSSEL NEE (BFAS correction Agusti-Panareda et al. ACP 2016)
- EDGARv4.2FT2010
- Takahashi et al. (2009)
- GFAS biomass burning
- IFS transport
- Bermejo & Conde mass fixer (Agusti-Panareda et al. GMD 2017)

Agusti-Panareda et al. ACP 2019

https://www.che-project.eu/news/animation-co2-variability
Global nature runs in 2015 – Reducing Model Error

<table>
<thead>
<tr>
<th>Components</th>
<th>CHE Tier 1 nature run</th>
<th>CHE Tier 2 nature run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface fluxes</td>
<td>Annual EDGARv4.2FT2010 anthropogenic, Takahashi et al. (2009) ocean, CTESSEL biogenic, GFAS fires</td>
<td>Monthly EDGARv4.3.2FT2015 anthropogenic (WP3) with daily residential heating (CAMS81) Rödenbeck et al (2013) ocean, CTESSEL biogenic, GFAS fires (CAMS)</td>
</tr>
<tr>
<td>Meteorological input data</td>
<td>Oper. ECMWF analysis</td>
<td>ERA-5 reanalysis</td>
</tr>
<tr>
<td>Initial conditions</td>
<td>CAMS analysis (20150101)</td>
<td>CAMS re-analysis (20141226)</td>
</tr>
<tr>
<td>Model version</td>
<td>IFS CY43R1 9km, 137 model levels</td>
<td>IFS CY46R1 9km and 25km, 137 model levels</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tagged tracers</td>
<td>$\text{CO}_2$ anthropogenic, biogenic, fires, ocean</td>
<td>$+\text{CO}_2$ sectorial emissions (power plants, manufacturing, residential heating, transport, other)</td>
</tr>
</tbody>
</table>

- Paper on high resolution global nature run in preparation
Evaluation of global nature runs (2015):

**Sodankyla, Finland**
- $\text{bias} = 0.59 \text{ std} = 1.82 \text{ rmse} = 1.92$
- $\delta = 1.02, \sigma = 0.97, r = 0.95$

**Garmish, Germany**
- $\text{bias} = 0.86 \text{ std} = 1.02 \text{ rmse} = 1.34$
- $\delta = 1.03, \sigma = 1.03, r = 0.87$

**South Pole**
- $\text{bias} = 0.33 \text{ std} = 0.96 \text{ rmse} = 1.02$
- $\delta = 1.62, \sigma = 1.02, r = 0.96$

**Lauder, New Zealand**
- $\text{bias} = -0.55 \text{ std} = 0.31 \text{ rmse} = 0.63$
- $\delta = 0.15, \sigma = 0.60, r = 0.94$

**Barrow, Alaska**
- $\text{bias} = -1.10 \text{ std} = 1.98 \text{ rmse} = 2.26$
- $\delta = 0.59, \sigma = 1.82, r = 1.92$

*obspack_co2_1_GLOBALVIEWplus_v5.0_2019-08-12*
Evaluation of global nature runs: synoptic to diurnal variability

Pasadena, California

Tier 1 NR
Tier 2 NR
Observations

S. Newman (CalTech)

Park Falls, Wisconsin

A. Andrews et al. (AMT, 2014)

Near surface CO2 [ppm]

\( \delta = 1.00 \sigma = 1.28, r = 0.68 \)

\( \delta = 1.37 \sigma = 1.50, r = 0.70 \)

Total column XCO2

\( \delta = 1.95 \sigma = 1.97, r = 0.31 \)

\( \delta = 0.61 \sigma = 1.64, r = 0.50 \)

Near surface CO2 [ppm]

\( \delta = -0.22 \sigma = 1.85, r = 1.86 \)

\( \delta = 1.48 \sigma = 2.00, r = 2.49 \)

Total column XCO2

\( \delta = -0.28 \sigma = 11.03, r = 11.03 \)

\( \delta = 1.97 \sigma = 9.98, r = 10.17 \)

\( \delta = 2.32 \sigma = 1.33, r = 0.65 \)

\( \delta = 1.06 \sigma = 1.24, r = 0.71 \)
Uncertainty Overview – Requirements for anthropogenic CO₂ inversion system

- Prior biogenic flux estimates or LSM process parameters.
- Prior anthropogenic flux estimates or FF process parameters.
- Observations.
- Initial atmospheric 3D CO₂ field.
- Meteorological conditions.
- Model physics.
- Representation Error.

- Multi-model spread or literature assessment (e.g. trait database) but no meteorological uncertainty.
- Rough estimates with little/no sector/country consideration.
- Reasonable knowledge of observation accuracy.
- Typically not considered.
- Typically not considered (with exceptions, see later).
- Typically not considered or inflation of observation.
- Typically not considered or inflation of observation.
EMISSION UNCERTAINTY – Dataset


Global gridded (0.1°×0.1° resolution) anthropogenic CO₂ 2015 emission uncertainties.

Aggregated in 7 main groups:
1) Super Power Stations
2) Energy Sector
3) Manufacturing
4) Settlements
5) Aviation
6) Non-Air Transport
7) Other

Based on IPCC (2006) and IPCC-TFI (2019) EF and AD uncertainty values. (Uncertainty in proxy data not included).

Uncertainties assumed perfect correlation within a country and no correlation between sectors and across borders.

Can be easily adapted for other years and datasets.
The diagram compares the emission budgets of the United Kingdom and France from different sources. The categories include energy, energy manufacturing, settlements, aviation, transport, and other sectors. The bars represent the estimated emissions, with error bars indicating the uncertainty bounds.

- **Our estimates (CHE)**
- **UNFCCC**
- **TNO v1.1 Tier 1**
- **TNO v1.1 Tier 2**

- Good agreement in emission budgets and uncertainties from different sources of emission data.
TRANSPORT UNCERTAINTY – Experimental Setup

Global ensemble simulations performed to investigate the following atmospheric CO$_2$ uncertainties:

- Initial Meteorological Conditions
- Biogenic Feedback to Transport Uncertainty
- Atmospheric Model Physics
- Emission Uncertainties

**Initial Concentration**
Informed from high resolution (~9km) IFS simulation

**Prior Emissions**
Perturbed inventory estimates based on uncertainties

**Meteorology**
Introduce tracers to current IFS-EPS framework

**Perturbed Ensemble Simulations**
- TCO399 (~25km)
- Hourly output
- January and July 2015
- Several experimental setups

**Ensemble-based Inversion System**
Test multiple inversion systems to estimate sector/national posterior fluxes
## TRANSPORT – Model Configurations

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial Conditions</th>
<th>Physics</th>
<th>Biogenic Emissions</th>
<th>Anthropogenic Emissions</th>
<th>Error Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>FME</td>
<td>EDA</td>
<td>SPPT on</td>
<td>Online</td>
<td>Fixed</td>
<td>Model (noise)</td>
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<tr>
<td>TME</td>
<td>EDA</td>
<td>SPPT on</td>
<td>Offline</td>
<td>Fixed</td>
<td>Transport</td>
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<tr>
<td>IME</td>
<td>EDA</td>
<td>SPPT off</td>
<td>Offline</td>
<td>Fixed</td>
<td>Initial meteorological</td>
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<tr>
<td>PME</td>
<td>Control</td>
<td>SPPT on</td>
<td>Offline</td>
<td>Fixed</td>
<td>Model physics</td>
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<tr>
<td>BME</td>
<td>Control</td>
<td>SPPT off</td>
<td>Offline-FME</td>
<td>Fixed</td>
<td>Biogenic feedback</td>
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<tr>
<td>PEM</td>
<td>Control</td>
<td>SPPT off</td>
<td>Online</td>
<td>Perturbed</td>
<td>Emission (signal)</td>
</tr>
<tr>
<td>PEA</td>
<td>Control</td>
<td>SPPT off</td>
<td>Online</td>
<td>Perturbed Annual Error</td>
<td>Anthropogenic emission (signal)</td>
</tr>
<tr>
<td>EXP</td>
<td>EDA</td>
<td>SPPT on</td>
<td>Online</td>
<td>Perturbed</td>
<td>Full PDF (signal &amp; noise)</td>
</tr>
</tbody>
</table>
TRANSPORT – Do We Accurately Represent Uncertainty?

Accounting for uncertainties in:
- Initial meteorology.
- Model physics.
- Biogenic feedback to meteorological uncertainty.
- Anthropogenic flux.

Over TCCON sites accounts for **21-65% of total error**.

The remaining error:
- Prior biogenic uncertainty.
- Observations.
- Initial 3D CO$_2$ field.
- Representation Error.
What Does Model XCO2 Uncertainty Look Like?

**Signal**: Prior emission spread

**Noise**: Remaining model uncertainty

High uncertainty (monthly emissions) provides **reasonable ratio over emission hotspots**.

Low uncertainty (annual emissions) shows low ratio, suggesting **small posterior error reduction**.
TRANSPORT – How Well Correlated are The Errors?

Average correlation length is variable with time.

Correlations variable dependant on location in time and distance.

Correlations show spurious noise for low ensemble sizes.

Correlations are flow-dependent.
CoCO2: Prototype system for a Copernicus CO2 service

IFS 4D-Var inversion of CO emissions

Posterior emission scaling factors

- Multi-scale: from global to local (high resolution capability)
- Multi-species: CO2, CH4, CO, NOx (use of satellite observations)

Integrated Forecasting System (IFS) at ECMWF:

- Prior anthropogenic emissions: modelling emissions residential heating with urban model, use of temporal and vertical profiles.
- Prior biogenic fluxes: new photosynthesis model, new land use cover and assimilation of observations (NRT LAI, SIF, VOD)
- Transport model: Testing new advection scheme and evaluation of plume dispersion
- Hybrid data assimilation system: optimal combination of adjoint-based and ensemble-based error covariance propagation.
SUMMARY

• CHE nature runs can provide a useful data set to explore observing system configuration requirements and modelling capabilities, as well as provide boundary conditions to regional models.

• New CoCO2 nature runs to be performed for 2016 and 2021.

• Plans for evaluation of CHE nature runs: use of aircraft data and OCO-2 XCO2.

• CHE nature runs will be made available in Copernicus Atmosphere Data Store (ADS) by end of 2020.

• Anthropogenic annual and monthly uncertainties have been derived for 7 sectors for 2015 for each country, with data available via Zenodo repository.

• A representation of model uncertainty and a “modest” prior anthropogenic uncertainty suggests the IFS-ENS can account for 21-65% of the total error. (also available via Zenodo).

• For monthly uncertainties signal-to-noise ratios are consistently above 1 over hotspots, but drop below 1 elsewhere.

• Work is on-going to reduce model error by improving priors and transport, and develop the multi-species inversion capability in the IFS within the CHE and CoCO2 project in cooperation with the Copernicus Atmosphere Service at ECMWF.