**SPECIAL PROJECT FINAL REPORT**

All the following mandatory information needs to be provided.

<table>
<thead>
<tr>
<th><strong>Project Title:</strong></th>
<th>Improve estimates of global and regional CH₄ and N₂O emissions based on inverse modelling using in-situ and satellite measurements</th>
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<tbody>
<tr>
<td><strong>Computer Project Account:</strong></td>
<td>spjrc4dv</td>
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<td><strong>Start Year - End Year :</strong></td>
<td>2015 - 2017</td>
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<tr>
<td><strong>Principal Investigator(s) :</strong></td>
<td>Dr. Peter Bergamaschi</td>
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</tbody>
</table>
| **Affiliation/Address:** | European Commission Joint Research Centre (EC-JRC)  
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Italy |
| **Other Researchers (Name/Affiliation):** | Dr. Mihai Alexe, EC-JRC (until 04/2016)  
Dr. Ernest Koffi, EC-JRC  
Dr. Arjo Segers, TNO Utrecht, Netherlands |
The following should cover the entire project duration.

**Summary of project objectives**  
(10 lines max)

1. Improve estimates of global CH₄ emissions using new satellite retrievals
2. Improve estimates of European CH₄ and N₂O emissions using in-situ observations
3. Improve TM5-4DVAR inverse modelling system

**Summary of problems encountered**  
(If you encountered any problems of a more technical nature, please describe them here.)

no major problems

**Experience with the Special Project framework**  
(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

Overall, the administrative procedures are straight-forward.  
The excellent technical support by the ECMWF user support team is highly appreciated.

**Summary of results**  
(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)
Improve estimates of global CH$_4$ emissions using new satellite retrievals

Global CH$_4$ flux inversions have been performed using four different GOSAT XCH$_4$ products from the Climate Research Data Package #4 (CRDP#4) of the GHG-CCI project (http://www.esa-ghg-cci.org/) of ESA’s Climate Change Initiative (CCI). The use of these four products in the TM5-4DVAR inverse modelling system results in qualitatively similar spatial distributions of the posteriori CH$_4$ fluxes (average 2010-2015) (Figure 1 and ESA Climate Assessment report version 4 [Chevallier et al., 2017]). Pronounced patterns in the inversion increments are the considerable emission increase over the South-Central United States, increase over tropical East Africa, and reductions over large parts of Southeast Asia compared to the prior emissions. There are, however, quantitative differences in the derived regional fluxes, especially in tropical regions for the inversions using the two proxy products (SRPR v2.3.8 and OCPR v7.0 compared to the inversions using the full physics XCH$_4$ products (SRFP v2.3.8 and OCFP v2.0.2), which are most likely largely related to the much lower number of retrievals of the full physics XCH$_4$ products close to the equator.

Additional global CH$_4$ flux inversions have been performed at higher horizontal resolution (3$^\circ$×2$^\circ$ instead of 6$^\circ$×4$^\circ$) and using different wetland CH$_4$ emission inventories, using updated inventories for the anthropogenic CH$_4$ emissions (EDGARv4.3.2), and different vertical convection schemes.

The global CH$_4$ flux inversions have been used in recent analyses of the global CH$_4$ budget and recent CH$_4$ trends within the international Global Carbon Project CH$_4$ initiative [Saunois et al., 2016; 2017]. The trend analysis showed that the global increase is mainly due to increased emissions from the tropics, with a smaller contribution from mid-latitudes and no significant change from boreal regions (consistent with our earlier analysis, based on the CH$_4$ inversions performed for MACC [Bergamaschi et al., 2013]). Furthermore, the analysis suggests that the "dominant contribution to the resumed atmospheric CH$_4$ growth after 2006 comes from microbial sources (more from agriculture and waste sectors than from natural wetlands), with an uncertain but smaller contribution from fossil CH$_4$ emissions" [Saunois et al., 2017].

The JRC TM5-4DVAR CH$_4$ flux inversions have been used also for validation of the Copernicus Atmosphere Monitoring Service (CAMS) CH$_4$ products, focussing on the "near-real time analyses" of the atmospheric CH$_4$ concentrations (from the ECMWF IFS assimilation system) and the re-analyses of GHG concentrations and fluxes (from the TM5-4DVAR inverse modelling system, provided by TNO / SRON) [Koffi and Bergamaschi, JRC technical report in preparation, 2018]. Since the JRC TM5-4DVAR inversion system was used as prototype of the operational CAMS inversion system, the comparisons of the CAMS and JRC CH$_4$ inversions provides a benchmark to evaluate the specific model setup and further model updates of the CAMS TM5-4DVAR system. The evaluation of the different inversions (by comparison with comprehensive independent observational data sets from surface monitoring stations, ship cruises, various aircraft programmes, AirCore soundings up to the middle stratosphere, and total column measurement) shows overall similar performance of the CAMS inversions (provided by TNO) and the JRC TM5-4DVAR CH$_4$ flux inversions.

Improve estimates of European CH$_4$ and N$_2$O emissions using in-situ observations

European CH$_4$ inversions have been performed using a new quality-controlled and harmonised in situ data set from 18 European atmospheric monitoring stations (generated within the European FP7 project InGOS ("Integrated non-CO2 Greenhouse gas Observing System")). These inversions (and further inversions from 6 other inverse modelling systems) have been analysed in a recent paper [Bergamaschi et al., 2018] (Figure 2). The analysis highlights the potential significant contribution of natural sources, such as peatlands, wetlands, and wet soils, estimated at 4.3 (2.3-8.2) Tg CH$_4$ yr$^{-1}$ for EU-28 from the "Wetland and Wetland CH4 Inter-comparison of Models Project" (WETCHIMP)
ensemble of 7 different wetland inventories [Melton et al., 2013; Wania et al., 2013], corresponding to 22% (11%-41%) of anthropogenic CH$_4$ emissions reported to UNFCCC. Furthermore, the analysis included a quantitative estimate of potential biases in the derived CH$_4$ emissions, by comparison with regular aircraft profiles at several European sites and based on the comparison of simulated and measured enhancements of CH$_4$ compared to the background, integrated over the entire boundary layer and over the lower troposphere. This analysis suggests that derived emissions may have regional bias ranging between -40 and 20% (based on aircraft profile sites in France, Hungary, and Poland). The mean bias over the larger European domain is probably smaller (but more aircraft measurements would be needed to confirm this).

Furthermore, N$_2$O inversions have been performed using the InGOS N$_2$O dataset from 13 European stations. The derived N$_2$O emissions for EU-28 are broadly consistent with the values reported to the UNFCCC within the very large uncertainties (~100%) of the reported values (Figure 3). The range of the top-down estimates of the applied model ensemble (TM5-4DVAR and further 3 models) is smaller than the uncertainty range of the bottom-up inventories, which demonstrates the potential of inverse modelling to significantly reduce the uncertainties in emission estimates.

**Improve TM5-4DVAR inverse modelling system**

During this project the modular TM5-pyshell 4DVAR version has been further developed and extensively tested and compared with the previous JRC TM5-4DVAR version. The TM5-4DVAR observation interface has been updated for the satellite observations (from the ESA GHG cci CRDP#4 products). The implementation of the 'Roedenbeck scheme' to calculate baseline concentrations in order to couple TM5-4DVAR with regional high-resolution models has been further developed in order to allow coupling with regional models with non-regular latitude / longitude grids as from the COSMO-FLEXPART system (which will be further developed and applied during the follow-up ECMWF special project "Improve European and global CH$_4$ and N$_2$O flux inversions" (2018-2020)).

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List of publications/reports from the project with complete references


**Future plans**

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

This research activity is further continued in the follow-up special project "Improve European and global CH₄ and N₂O flux inversions" (2018-2020).
Figure 1: CH₄ emissions (average 2010-2015) derived from global inversions based on TM5-4DVAR inverse modelling system. Upper left map shows the applied prior emissions, and the subsequent rows the posteriori emissions (left) and the inversion increments (difference between posterior and prior emissions; right) for the inversions of four GOSAT products from the Climate Research Data Package #4 (CRDP#4) of the ESA GHG cci project - second phase [Chevallier et al., 2017].
Figure 2: Estimates of European CH$_4$ emissions derived from 7 inverse models [Bergamaschi et al., 2018]. Annual total CH$_4$ emissions derived from inversions for northern, western, eastern, and southern Europe, and for EU-28 (coloured symbols; bars show estimated 2$\sigma$ uncertainties). For comparison, anthropogenic CH$_4$ emissions reported to UNFCCC (black line; grey range: 2$\sigma$ uncertainty estimate based on National Inventory Reports), and from EDGARv4.2FT-InGOS (black stars) are shown. Furthermore, the blue lines show wetland CH$_4$ emissions from the WETCHIMP ensemble of seven models (mean, blue solid line; median, blue dashed line; minimum–maximum range, light-blue range).
Figure 3: Estimates of European N₂O emissions derived from 4 inverse models (coloured symbols). Anthropogenic N₂O emissions reported to UNFCCC (submission 2017) are shown by the black line and the estimate of natural soil N₂O emissions [Bouwman et al., 1995] are shown by the blue dashed line.