SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Improve estimates of global and regional CH_4 and N_2O emissions based on inverse modelling using in-situ and satellite measurements
Computer Project Account:	spjrc4dv
Start Year - End Year :	2015 - 2017
Principal Investigator(s)	Dr. Peter Bergamaschi
Affiliation/Address:	European Commission Joint Research Centre (EC-JRC) Directorate for Energy, Transport and Climate Air and Climate Unit TP 124 I-21027 Ispra (Va) 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 CH_4 emissions using new satellite retrievals**

2. **Improve estimates of European CH_4 and N_2O 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 ($3^o \times 2^o$ instead of $6^o \times 4^o$) 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[1]]. 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_2O 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_2O inversions have been performed using the InGOS N_2O dataset from 13 European stations. The derived N_2O 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_2O flux inversions" (2018-2020)).

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[1] Bergamaschi, P., et al., Atmospheric CH_4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, J. Geophys. Res.-Atmos., 118, 7350–7369, https://doi.org/10.1002/jgrd.50480, 2013.

List of publications/reports from the project with complete references

Bergamaschi, P., U. Karstens, A. J. Manning, M. Saunois, A. Tsuruta, A. Berchet, A. T. Vermeulen, T. Arnold, G. Janssens-Maenhout, S. Hammer, I. Levin, M. Schmidt, M. Ramonet, M. Lopez, J. Lavric, T. Aalto, H. Chen, D. G. Feist, C. Gerbig, L. Haszpra, O. Hermansen, G. Manca, J. Moncrieff, F. Meinhardt, J. Necki, M. Galkowski, amp, apos, S. Doherty, N. Paramonova, H. A. Scheeren, M. Steinbacher, and E. Dlugokencky, Inverse modelling of European CH_4 emissions during 2006–2012 using different inverse models and reassessed atmospheric observations, Atmos. Chem. Phys., 18(2), 901-920, doi: 10.5194/acp-18-901-2018, 2018.

Bruhwiler, L. M., S. Basu, P. Bergamaschi, P. Bousquet, E. Dlugokencky, S. Houweling, M. Ishizawa, H. S. Kim, R. Locatelli, S. Maksyutov, S. Montzka, S. Pandey, P. K. Patra, G. Petron, M. Saunois, C. Sweeney, S. Schwietzke, P. Tans, and E. C. Weatherhead, U.S. CH_4 emissions from oil and gas production: Have recent large increases been detected?, J. Geophys. Res.-Atmos., 122(7), 4070-4083, doi: 10.1002/2016jd026157, 2017.

Chevallier, F., P. Bergamaschi, D. Brunner, L. Feng, S. Houweling, T. Kaminski, W. Knorr, J. Marshall, P. I. Palmer, S. Pandey, M. Reuter, M. Scholze, and M. Voßbeck, Climate Assessment Report for the GHG-CCI project of ESA's Climate Change Initiative, version 4, 28 March 2017, 96 pp, http://www.esa-ghg-cci.org/?q=webfm_send/385, 2017.

Houweling, S., P. Bergamaschi, F. Chevallier, M. Heimann, T. Kaminski, M. Krol, A. M. Michalak, and P. Patra, Global inverse modeling of CH_4 sources and sinks: an overview of methods, Atmos. Chem. Phys., 17(1), 235-256, doi: 10.5194/acp-17-235-2017, 2017.

Koffi, E. N., P. Bergamaschi, U. Karstens, M. Krol, A. Segers, M. Schmidt, I. Levin, A. T. Vermeulen, R. E. Fisher, V. Kazan, H. Klein Baltink, D. Lowry, G. Manca, H. A. J. Meijer, J. Moncrieff, S. Pal, M. Ramonet, H. A. Scheeren, and A. G. Williams, Evaluation of the boundary layer dynamics of the TM5 model over Europe, Geosci. Model Dev., 9, 3137-3160, doi: 10.5194/gmd-9-3137-2016, 2016.

Saunois, M., P. Bousquet, B. Poulter, A. Peregon, P. Ciais, J. G. Canadell, E. J. Dlugokencky, G. Etiope, D. Bastviken, S. Houweling, G. Janssens-Maenhout, F. N. Tubiello, S. Castaldi, R. B. Jackson, M. Alexe, V. K. Arora, D. J. Beerling, P. Bergamaschi, D. R. Blake, G. Brailsford, L. Bruhwiler, C. Crevoisier, P. Crill, K. Covey, C. Frankenberg, N. Gedney, L. Höglund-Isaksson, M. Ishizawa, A. Ito, F. Joos, H. S. Kim, T. Kleinen, P. Krummel, J. F. Lamarque, R. Langenfelds, R. Locatelli, T. Machida, S. Maksyutov, J. R. Melton, I. Morino, V. Naik, S. O'Doherty, F. J. W. Parmentier, P. K. Patra, C. Peng, S. Peng, G. P. Peters, I. Pison, R. Prinn, M. Ramonet, W. J. Riley, M. Saito, M. Santini, R. Schroeder, I. J. Simpson, R. Spahni, A. Takizawa, B. F. Thornton, H. Tian, Y. Tohjima, N. Viovy, A. Voulgarakis, R. Weiss, D. J. Wilton, A. Wiltshire, D. Worthy, D. Wunch, X. Xu, Y. Yoshida, B. Zhang, Z. Zhang, and Q. Zhu, Variability and quasi-decadal changes in the methane budget over the period 2000–2012, Atmos. Chem. Phys., 17(18), 11135-11161, doi: 10.5194/acp-17-11135-2017, 2017.

Saunois, M., P. Bousquet, B. Poulter, A. Peregon, P. Ciais, J. G. Canadell, E. J. Dlugokencky, G. Etiope, D. Bastviken, S. Houweling, G. Janssens-Maenhout, F. N. Tubiello, S. Castaldi, R. B. Jackson, M. Alexe, V. K. Arora, D. J. Beerling, P. Bergamaschi, D. R. Blake, G. Brailsford, V. Brovkin, L. Bruhwiler, C. Crevoisier, P. Crill, K. Covey, C. Curry, C. Frankenberg, N. Gedney, L. Höglund-Isaksson, M. Ishizawa, A. Ito, F. Joos, H.-S. Kim, T. Kleinen, P. Krummel, J.-F. Lamarque, R. Langenfelds, R. Locatelli, T. Machida, S. Maksyutov, K. C. McDonald, J. Marshall, J. R. Melton, I. Morino, V. Naik, S. O'Doherty, F.-J. W. Parmentier, P. K. Patra, C. Peng, S. Peng, G. P. Peters, I. Pison, C. Prigent, R. Prinn, M. Ramonet, W. J. Riley, M. Saito, M. Santini, R. Schroeder, I. J. Simpson, R. Spahni, P. Steele, A. Takizawa, B. F. Thornton, H. Tian, Y. Tohjima,

N. Viovy, A. Voulgarakis, M. van Weele, G. R. van der Werf, R. Weiss, C. Wiedinmyer, D. J. Wilton, A. Wiltshire, D. Worthy, D. Wunch, X. Xu, Y. Yoshida, B. Zhang, Z. Zhang, and Q. Zhu, The global methane budget 2000-2012, Earth System Science Data, 8(2), 697-751, doi: 10.5194/essd-8-697-2016, 2016.

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 CH_4 and N_2O flux inversions" (2018-2020).

Figures

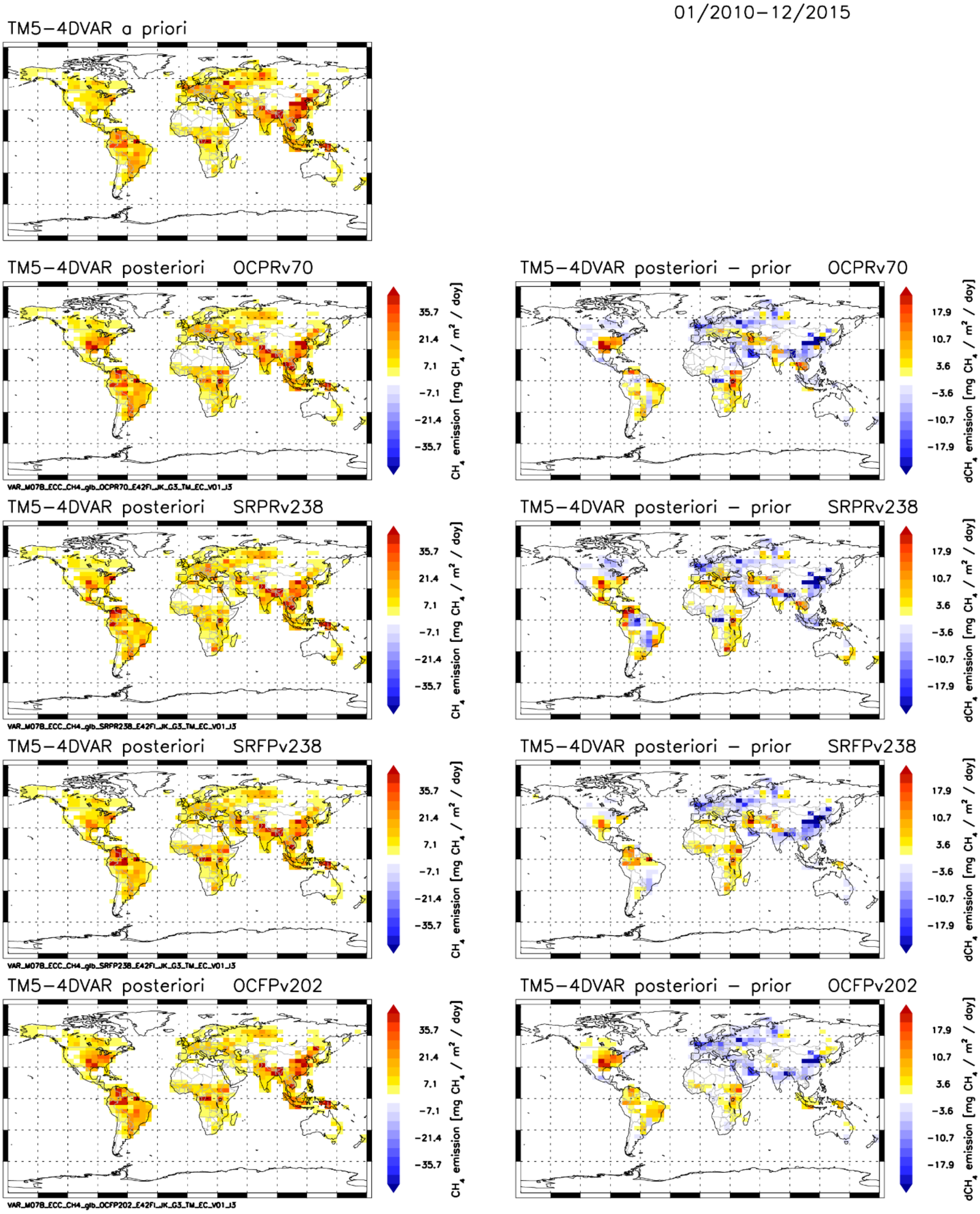

Figure 1: CH_4 emissions (average 2010-2015) derived from global inversions based on TM5-4DVAR inverse modelling system. Upper left map shows the applied prior emissions, and the subsequent rows the posteriori emissions (left) and the inversion increments (difference between posterior and prior emissions; 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].

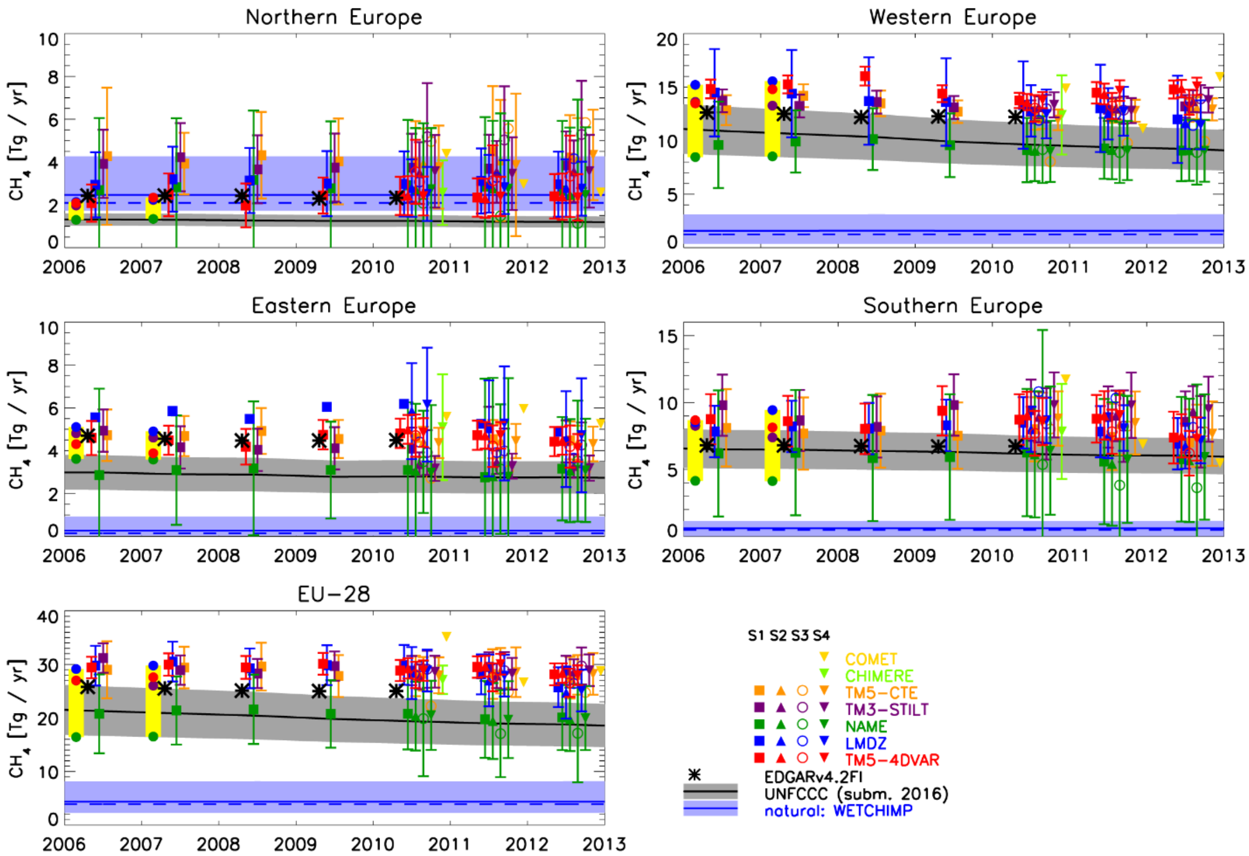

Figure 2: Estimates of European CH_4 emissions derived from 7 inverse models [*Bergamaschi et al.,* 2018]. Annual total CH_4 emissions derived from inversions for northern, western, eastern, and southern Europe, and for EU-28 (coloured symbols; bars show estimated 2σ uncertainties). For comparison, anthropogenic CH_4 emissions reported to UNFCCC (black line; grey range: 2σ 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).

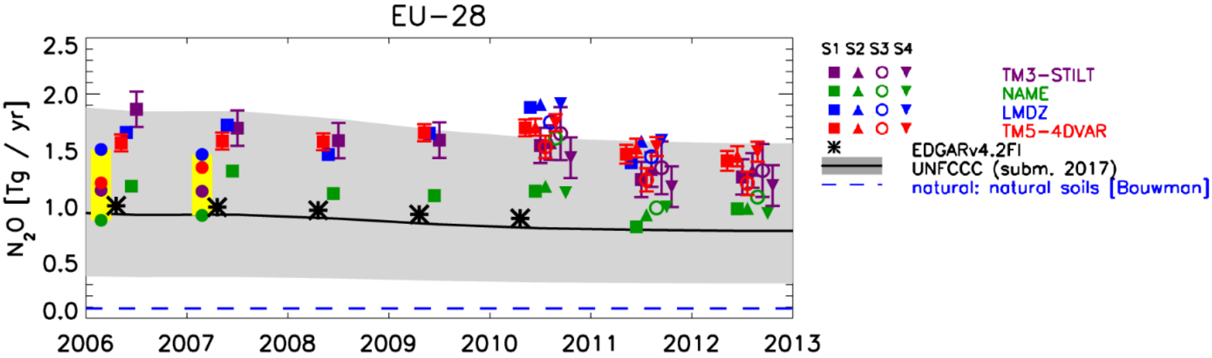

Figure 3: Estimates of European N_2O emissions derived from 4 inverse models (coloured symbols). Anthropogenic N_2O emissions reported to UNFCCC (submission 2017) are shown by the black line and the estimate of natural soil N_2O emissions [*Bouwman et al.*, 1995] are shown by the blue dashed line.