SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Improve European and global CH_4 and N_2O flux inversions
Computer Project Account:	spjrc4dv
Start Year - End Year :	2018 - 2020
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. 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. Develop coupled global / regional inversion system with high spatial resolution

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, reflecting the complexity and duration of the project, 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

Various series of global CH_4 flux inversions have been performed using the TM5-4DVAR inverse modelling system at horizontal resolutions of 6°×4° and 3°×2°, assimilating surface observations (from NOAA Earth System Research Laboratory (ESRL) global cooperative air sampling network 2000-2018), and satellite retrievals of column-average dry-air mole fractions (XCH_4) from GOSAT (2010-2018). Figure 1 shows a comparison of an inversion including GOSAT data (GOSAT OCPRv7.2 product) with an inversion using only surface observations, illustrating the impact of the satellite data on the derived CH_4 emissions. While the surface observations from remote background stations provide information on emissions mainly on larger continental scales, the GOSAT satellite retrievals provide additional constraints on regional scales.
These inversions have been used for validation of the Copernicus Atmosphere Monitoring Service (CAMS) CH_4 products [Koffi and Bergamaschi, 2018]. Since the JRC TM5-4DVAR inversion system was used as prototype of the operational CAMS inversion system, the comparison 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. Overall, the comparison showed good consistency between the JRC and CAMS TM5-4DVAR systems. In addition, the "NOAA-only" inversions have been used to evaluate the latest release (v9.0) of the University of Leicester GOSAT Proxy XCH_4 dataset [Parker et al., 2020].
Furthermore, the global CH_4 flux inversions (together with CH_4 flux inversions from other research groups) have been used in a detailed analysis of the global CH_4 budget [Saunois et al., 2020; Jackson et al., 2020] in the framework of the Global Carbon Project CH_4 (GCP-CH_4; https://www.globalcarbonproject.org/methanebudget/). From this analysis it has been estimated that global CH_4 emissions in 2017 were about 9% (50 Tg CH_4 yr^{-1}) higher than the average for the period 2000–2006 (546 Tg CH_4 yr^{-1}, range 538–555 Tg CH_4 yr^{-1}), with the increase attributable primarily to an increase in anthropogenic emissions, mainly (approximately equally) from agricultural and fossil fuel sources [Jackson et al., 2020].
Moreover, the global CH_4 flux inversions were used to derive an observation-driven estimate of the climate sensitivity of wetland methane emissions [Koffi et al., 2020], analysing the response functions of CH_4 fluxes (derived in the inversion) to observed temperature and precipitation. The derived climate sensitivity has been used to estimate the increase of wetland CH_4 emissions by 2100 under different climate scenarios [Koffi et al., 2020], resulting in a projected increase by 50 to 80% under the RCP 8.5 ("business-as-usual") climate scenario.

Improve estimates of European CH_4 and N_2O emissions using in-situ observations

Within the H2020 project VERIFY ("Observation-based system for monitoring and verification of greenhouse gases"; http://verify.lsce.ipsl.fr/) various CH_4 inversions with zoom over Europe have been performed, contributing to the annual analysis cycles within VERIFY (2018, 2019, 2020). The results from the 2nd analysis cycle (2019) have been used in a recent synthesis of European CH_4 emissions [Petrescu et al., 2021], including a comprehensive comparison between different inverse models and various bottom-up inventories for natural and anthropogenic emissions. The analysis highlighted the non-negligible contribution of natural sources, which need to be considered when comparing top-down estimates of total emissions with anthropogenic emissions reported to UNFCCC (which are based on statistical bottom-up data), consistent with an earlier analysis of European flux inversions [Bergamaschi et al., 2018].
Current bottom-up estimates of natural emissions performed in VERIFY, however, may overestimate natural emissions in some regions, as suggested by the significant negative inversion increments over large parts of Europe (3rd cycle of VERIFY inversions, using the complete set of VERIFY bottom-up inventories for anthropogenic and natural emission sources; Figure 2).

Develop coupled global / regional inversion system with high spatial resolution

The coupled FLEXPART-COSMO / TM5 4DVAR inverse modelling system ("FLEXVAR") has been developed (main model development: Arjo Segers, TNO; FLEXPART-COSMO simulations: Dominik Brunner, EMPA). FLEXVAR is based on a variational (4DVAR) system (as in TM5-4DVAR), using FLEXPART back trajectories driven by meteorological fields from the COSMO-7 numerical weather prediction system at a horizontal resolution of 7 km × 7 km and baselines from global / European TM5-4DVAR inversions. Major development steps included:
- implementation of 4DVAR inversion framework, using alternatively m1qn3 or conjugate gradient optimisation algorithms.
- development of observation operator to allow the use of observational data sets from multiple stations.
- development of interface to allow the use of different emission inventories as prior emission estimates.
- implementation and testing of different approaches to estimate the model representation error.

Figure 3 shows as example a FLEXVAR inversion for 2018 using EDGARv5.0 (2015) as prior and a comprehensive observational data set of 20 European atmospheric stations.
Detailed tests of the FLEXVAR system demonstrated that the inversions are performed in a technically correct way, as indicated by the achieved significant reduction in the gradient norm of the cost function and the significant improvement of the statistics of the simulated vs. observed station data (correlation, bias, RMS difference).

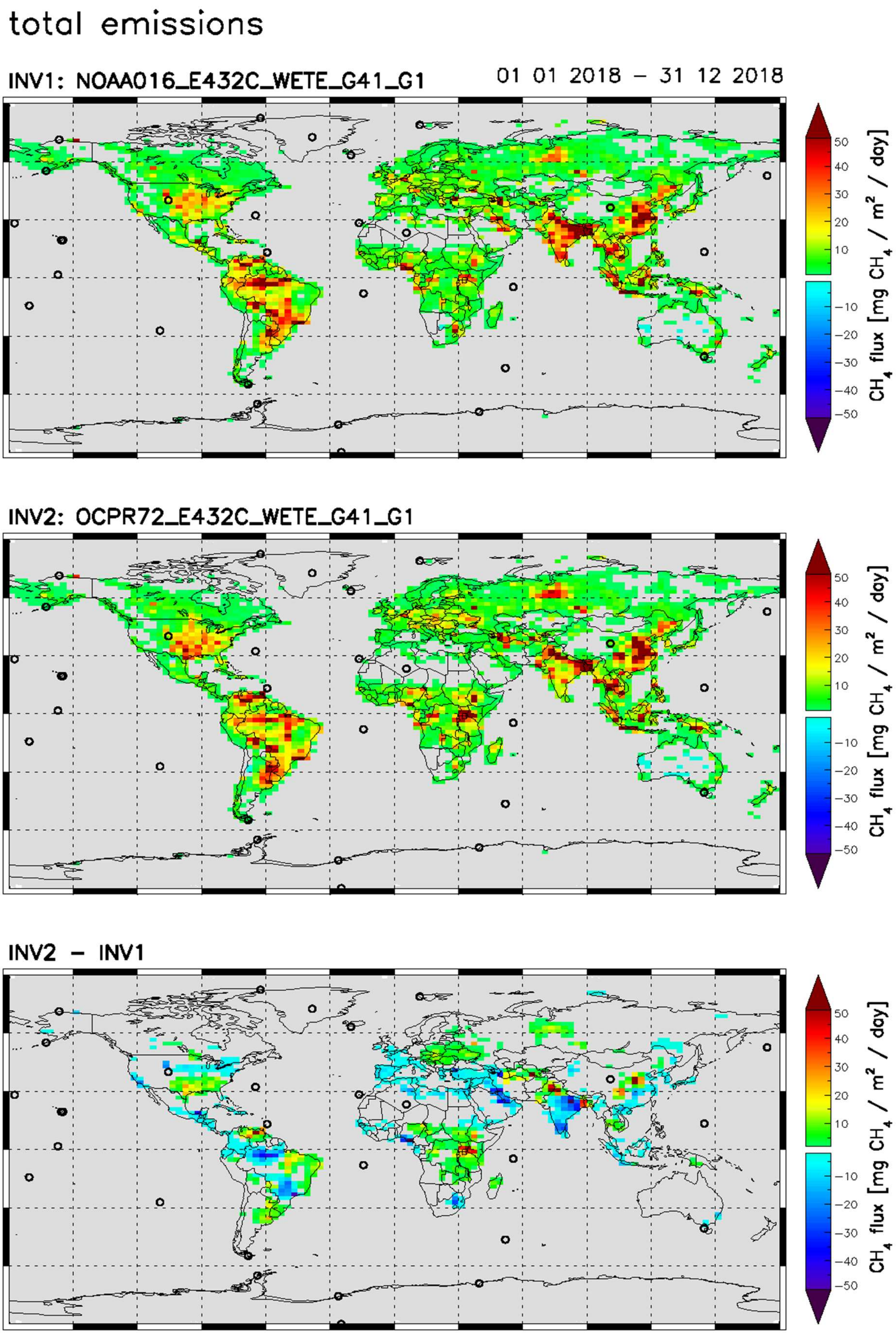

Figure 1: Derived (a posteriori) total CH_4 emissions for 2018. Top: INV1 including only NOAA surface observations. Middle: inversion INV2 using both NOAA surface observations and XCH_4 satellite retrievals from GOSAT. Bottom: Difference between INV2 and INV1. The open circles show the locations of the NOAA discrete air sampling sites used in the inversion.

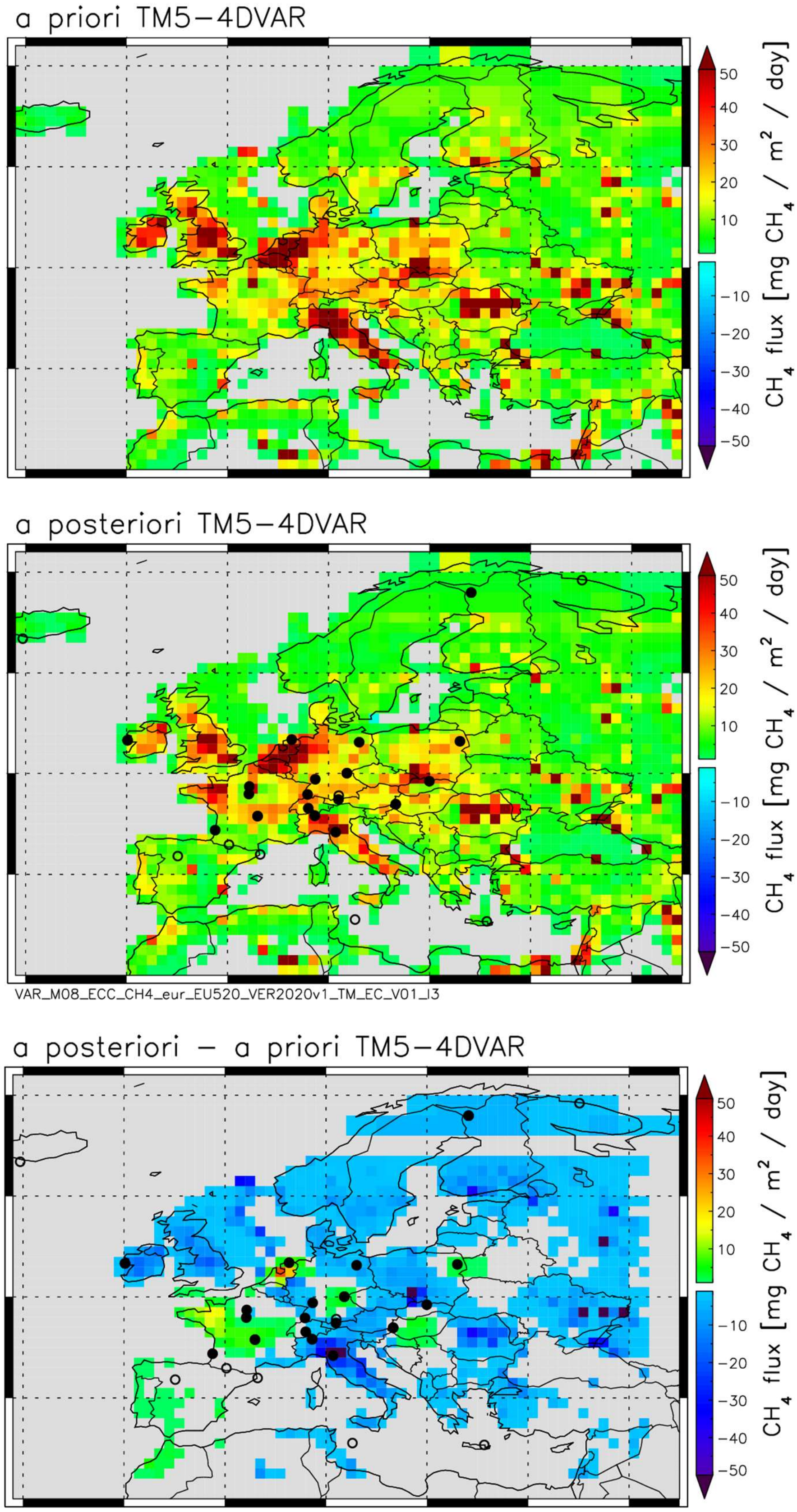

Figure 2: Estimate of European CH_4 emissions (average 2005-2018) using TM5-4DVAR model and input data according to VERIFY inversion protocol 2020 (3rd cycle of VERIFY inversions), including complete set of VERIFY bottom-up inventories for anthropogenic and natural emission sources. Top: a priori emissions. Middle: a posteriori emissions. Bottom: difference between a posteriori and a priori. Black circles show locations of measurement stations used in the inversion; filled circles: stations with quasi-continuous measurements; open circles: discrete air sampling sites.

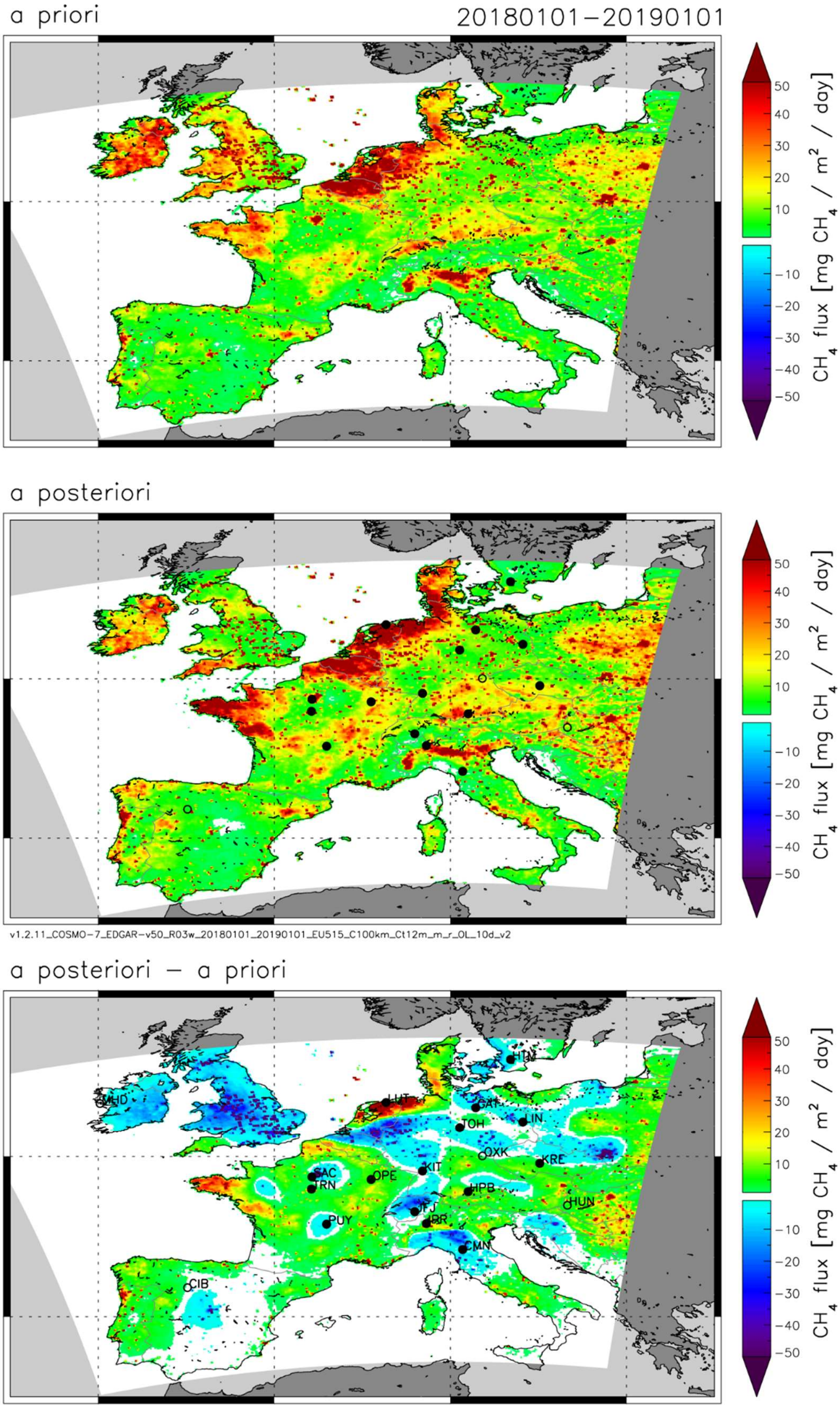

Figure 3: Inverse modelling of European CH_4 emissions with high-resolution FLEXVAR inverse modelling system. The FLEXVAR system uses FLEXPART-COSMO-7 backtrajectories at a resolution of about 7 km × 7 km. Top: a priori emissions (EDGARv5.0; no natural emissions used in this test inversion). Middle: a posteriori emissions. Bottom: difference between a posteriori and a priori. Black circles show locations of measurement stations used in the inversion; filled circles: stations with quasi-continuous measurements; open circles: discrete air sampling sites.

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.

Bergamaschi, P., D. Brunner, R. Thompson, P. Bousquet, Top-down estimates of European CH_4 emissions during 2005-2016 using two different inverse models, oral presentation at 8th International Symposium on Non-CO2 Greenhouse Gases, June 12-14, 2019, Amsterdam, The Netherlands, 2019.

Koffi, E.N. and Bergamaschi, P., Evaluation of Copernicus Atmosphere Monitoring Service methane products, EUR 29349 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-93409-4, doi:10.2760/906932, JRC112816, 2018.

Koffi, E. N., Bergamaschi, P., Alkama, R., and Cescatti, A., An observation-constrained assessment of the climate sensitivity and future trajectories of wetland methane emissions, Science Advances 10 Apr 2020: Vol. 6, no. 15, eaay4444, DOI: 10.1126/sciadv.aay4444, 2020.

Koren, G., Schneider, L., van der Velde, I. R., van Schaik, E., Gromov, S. S., Adnew, G. A., Martino, D. J. M., Hofmann, M. E. G., Liang, M.-C., Mahata , S., Bergamaschi, P., van der Laan-Luijkx, I. T., Krol, M. C., Röckmann, T., and Peters, W., Global 3-D simulations of the triple oxygen isotope signature $\Delta^{17}O$ in atmospheric CO_2, Journal of Geophysical Research: Atmospheres, 124, 8808–8836. https://doi.org/10.1029/2019JD030387, 2019.

Jackson, R. B., M. Saunois, P. Bousquet, J. G. Canadell, B. Poulter, A. R. Stavert, P. Bergamaschi, Y. Niwa, A. Segers, and A. Tsuruta, Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources, Environ. Res. Lett. 15 071002, 2020.

Parker, R. J., Webb, A., Boesch, H., Somkuti, P., Barrio Guillo, R., Di Noia, A., Kalaitzi, N., Anand, J. S., Bergamaschi, P., Chevallier, F., Palmer, P. I., Feng, L., Deutscher, N. M., Feist, D. G., Griffith, D. W. T., Hase, F., Kivi, R., Morino, I., Notholt, J., Oh, Y.-S., Ohyama, H., Petri, C., Pollard, D. F., Roehl, C., Sha, M. K., Shiomi, K., Strong, K., Sussmann, R., Té, Y., Velazco, V. A., Warneke, T., Wennberg, P. O., and Wunch, D.: A decade of GOSAT Proxy satellite CH_4 observations, Earth Syst. Sci. Data, 12, 3383–3412, https://doi.org/10.5194/essd-12-3383-2020, 2020.

Petrescu, A. M. R., Qiu, C., Ciais, P., Thompson, R. L., Peylin, P., McGrath, M. J., Solazzo, E., Janssens-Maenhout, G., Tubiello, F. N., Bergamaschi, P., Brunner, D., Peters, G. P., Höglund-Isaksson, L., Regnier, P., Lauerwald, R., Bastviken, D., Tsuruta, A., Winiwarter, W., Patra, P. K., Kuhnert, M., Oreggioni, G. D., Crippa, M., Saunois, M., Perugini, L., Markkanen, T., Aalto, T., Groot Zwaaftink, C. D., Tian, H., Yao, Y., Wilson, C., Conchedda, G., Günther, D., Leip, A., Smith, P., Haussaire, J.-M., Leppänen, A., Manning, A. J., McNorton, J., Brockmann, P., and Dolman, A. J.: The consolidated European synthesis of CH_4 and N_2O emissions for the European Union and United Kingdom: 1990–2017, Earth Syst. Sci. Data, 13, 2307–2362, https://doi.org/10.5194/essd-13-2307-2021, 2021.

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q., and Zhuang, Q.: The Global Methane Budget 2000–2017, Earth Syst. Sci. Data, 12, 1561–1623, https://doi.org/10.5194/essd-12-1561-2020, 2020.

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.)

The FLEXVAR model development will be continued / finalised in the new Special Project "Extend and improve CH_4 flux inversions at global and European scale" (2021; PI: Dr. Ernest Koffi).