SPECIAL PROJECT PROGRESS REPORT

Progress Reports should be 2 to 10 pages in length, depending on importance of the project. All the following mandatory information needs to be provided.

Reporting year	2019 (01 July 2018 - 30 June 2019)
Project Title:	Improve European and global CH_4 and N_2O flux inversions
Computer Project Account:	spjrc4dv
Principal Investigator(s):	Dr. Peter Bergamaschi
Affiliation:	European Commission Joint Research Centre (EC-JRC) Directorate for Energy, Transport and Climate Air and Climate Unit TP 124 I-21027 Ispra (Va) Italy
Name of ECMWF scientist(s) collaborating to the project (if applicable)	Dr. Anna Agusti-Panareda (in the framework of the Copernicus / CAMS project)
Start date of the project:	01 January 2018
Expected end date:	31 December 2020

Computer resources allocated/used for the current year and the previous one

(if applicable)
Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	400000	387120	400000	5934 (28 June 2019)
Data storage capacity	(Gbytes)	400		800	

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 any)
(20 lines max)

no major problems

Summary of results of the current year (from July of previous year to June of current year)
This section should comprise 1 to 8 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

A new series of global CH_4 flux inversions has been performed following the modelling protocol of the Global Carbon Project CH_4 (GCP-CH_4; https://www.globalcarbonproject.org/methanebudget/). The inversions assimilate either (1) only surface observations (from NOAA Earth System Research Laboratory (ESRL) global cooperative air sampling network), denoted inversion 'Inv1 (NOAA)', or (2) both surface observations and satellite retrievals of column-average dry-air mole fractions (XCH_4) from GOSAT (using the GOSAT OCPRv7.2 product [Parker, 2016], denoted inversion 'Inv2 (OCPR)'.
Figure 1 shows the derived (a posteriori) CH_4 emissions for both inversions (average CH_4 emissions for 2010-2017). The significant differences in the derived spatial emission patterns between the two inversions are due to the different observational constraints: 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. Major significant differences between the two inversions are in particular the higher derived CH_4 emissions over the central-south United States, lower emissions in western equatorial Africa (Congo basin), higher emissions in eastern equatorial Africa, and lower emissions in the Persian Gulf area in 'Inv2 (OCPR)' compared to 'Inv1 (NOAA)'. Over the United States, similar emission patterns had been reported in earlier studies, both using the TM5-4DVAR system at coarser resolution ($6^o \times 4^o$) [Alexe et al., 2015] and in independent studies using higher resolution regional inversion systems and regional surface and aircraft observations [Miller et al., 2013].
Figure 2 shows the time series of observed and simulated CH_4 dry air mole fractions at some representative remote global NOAA monitoring stations, demonstrating the overall excellent agreement between a posteriori model simulations and observations. Furthermore, the figure illustrates that the simulated station time series of 'Inv2 (OCPR)' are very similar to those of 'Inv1 (NOAA)', which demonstrates that the regional inversion increments induced by the GOSAT XCH_4 retrievals can be largely reconciled with the continental scale constraints from the high-accuracy surface observations.
Figure 3 shows the time series of XCH_4 retrievals and assimilated XCH_4.. The figure demonstrates the overall very good agreement between retrievals and model simulations (please note, that similar to previous studies we applied a bias correction of the XCH_4 retrievals as function of latitude and month [Bergamaschi et al., 2013; Alexe et al., 2015]). However, Figure 3 (3rd panel) also shows a small regular residual as function of latitude and season (on the order of a few ppb), indicating that some remaining retrieval and / or model errors cannot be fully compensated by the bias correction.
In further sensitivity studies we investigated the impact of using different a priori emission inventories, in particular comparing inversions using the time dependent CH_4 inventories provided by GCP-CH_4 with inversions using the same a priori inventories for all years, showing that the derived trends of global total emissions are largely independent from the applied a priori inventory, but the derived partitioning between different major source categories are partly sensitive on the applied a priori (results not shown).
The model results were submitted to the GCP-CH_4 project and have been used in an updated analysis of the global CH_4 budget, which will be presented in a comprehensive publication of the GCP-CH_4 group [Saunois et al., 2019].
Furthermore, the new inversions are used for the further validation of the Copernicus Atmosphere Monitoring Service (CAMS) CH_4 products (updating and extending the previous report [*Koffi and Bergamaschi*, 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.

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/) first CH_4 inversions have been performed, following the VERIFY modelling protocol and common input data sets (a priori emission inventories and observational data).
Figure 4 shows the derived European CH_4 emissions (average of 2005-2016) of these first preliminary inversions. Compared to previous studies [e.g. Bergamaschi et al., 2018] the time series has been significantly extended (covering now 12 years). However, many stations do not cover the full 2005-2016 period. Therefore, the derived CH_4 emissions are probably partly affected by incomplete temporal data coverage. This particular issue will be further investigated in the 2nd series of VERIFY inversions, which will be performed in the coming months (using updated observational data sets).
The first TM5-4DVAR CH_4 inversion have been also used to extract 'baselines' for the EMPA FLEXPART - extended Kalman-filter system (FLEXPART-eKF) [Brunner et al., 2012], using the "Rödenbeck scheme" [Rödenbeck et al., 2009] (also in the framework of the VERIFY project). FLEXPART-eKF is a regional modelling system limited over the European domain and relies on the provision of realistic boundary conditions or 'baselines' (which are the concentrations at the measurement stations in absence of emissions from the regional domain). The default approach of FLEXPART-eKF is to estimate the baselines during the inversion (including the baseline in the state vector). Our study showed that using the TM5-4DVAR baselines instead of the 'default' baselines has a large impact on the CH_4 emissions derived by FLEXPART-eKF. The first VERIFY CH_4 inversions (including the study on the impact of using different baselines) have been presented at the 8th International Symposium on Non-CO_2 Greenhouse Gases (June 12-14, 2019, Amsterdam, The Netherlands) [Bergamaschi et al., 2019].

The 2nd series of VERIFY inversions will use updated a priori emission inventories and extended observational data sets, and will be extended until end of 2017. Furthermore the new inversion series will analyse the use of more consistent observational data set over certain sub-periods (with more complete data coverage) to allow also a better analysis of emission trends.

Develop coupled global / regional inversion system with high spatial resolution

First CH_4 inversions have been performed using a regional 4DVAR prototype inverse modelling system based on the regional Lagrangian particle dispersion model FLEXPART, coupled to the TM5-4DVAR inverse modelling system (main model development: Arjo Segers, TNO; FLEXPART simulations: Dominik Brunner, EMPA). In contrast to FLEXPART simulations mentioned in the previous section (which were driven by ECMWF ERA-INTERIM meteorological fields), here a specific high-resolution version of FLEXPART (developed by EMPA) is employed, driven by meteorological fields from the COSMO-7 numerical weather prediction system at a horizontal resolution of 7 km [Henne et al., 2016]. The coupling between the regional FLEXPART/ COSMO-7 system and the global TM5-4DVAR inverse modelling system is based on the method of Rödenbeck et al. [2009] (similarly as described above for the FLEXPART-eKF system).
First results were presented at the 3rd ICOS Science Conference, Prague, 11-13 September 2018 [Bergamaschi et al., 2018].

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., A. Segers, G. Manca, and D. Brunner, High-resolution inverse modelling of CH_4 emissions around monitoring station Ispra, Italy - first results, poster presented at 3rd ICOS Science Conference, Prague, 11-13 September 2018.

Bergamaschi, P., D. Brunner, R. Thompson, P. Bousquet, Top-down estimates of European CH4 emissions during 2005-2016 using two different inverse models, oral presentation at 8th International Symposium on Non-CO_2 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.

Saunois, M., et al., The Global Methane Budget 2000-2017, manuscript in preparation, 2019.

Further references

Alexe, M., Bergamaschi, P., Segers, A., Detmers, R., Butz, A., Hasekamp, O., Guerlet, S., Parker, R., Boesch, H., Frankenberg, C., Scheepmaker, R. A., Dlugokencky, E., Sweeney, C., Wofsy, S. C., and Kort, E. A.: Inverse modelling of CH_4 emissions for 2010–2011 using different satellite retrieval products from GOSAT and SCIAMACHY, Atmos. Chem. Phys., 15, 113–133, https://doi.org/10.5194/acp-15-113-2015, 2015.

Bergamaschi, P., Houweling, S., Segers, A., Krol, M., Frankenberg, C., Scheepmaker, R. A., Dlugokencky, E., Wofsy, S. C., Kort, E. A., Sweeney, C., Schuck, T., Brenninkmeijer, C., Chen, H., Beck, V., and Gerbig, C.: 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, doi:10.1002/jgrd.50480, 2013.

Bergamaschi, P., A. Danila, R. F. Weiss, P. Ciais, R. L. Thompson, D. Brunner, I. Levin, Y. Meijer, F. Chevallier, G. Janssens-Maenhout, H. Bovensmann, D. Crisp, S. Basu, E. Dlugokencky, R. Engelen, C. Gerbig, D. Günther, S. Hammer, S. Henne, S. Houweling, U. Karstens, E. Kort, M. Maione, A. J. Manning, J. Miller, S. Montzka, S. Pandey, W. Peters, P. Peylin, B. Pinty, M. Ramonet, S. Reimann, T. Röckmann, M. Schmidt, M. Strogies, J. Sussams, O. Tarasova, J. van Aardenne, A. T. Vermeulen, F. Vogel, Atmospheric monitoring and inverse modelling for verification of greenhouse gas inventories, EUR 29276 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-88938-7, doi:10.2760/759928, JRC111789, 2018.

Brunner, D., S. Henne, C. A. Keller, S. Reimann, M. K. Vollmer, S. O'Doherty, and M. Maione, An extended Kalman-filter for regional scale inverse emission estimation, Atmos. Chem. Phys., 12(7), 3455-3478, doi:10.5194/acp-12-3455-2012, 2012.

Henne, S., D. Brunner, B. Oney, M. Leuenberger, W. Eugster, I. Bamberger, F. Meinhardt, M. Steinbacher, and L. Emmenegger, Validation of the Swiss methane emission inventory by atmospheric observations and inverse modelling, Atmos. Chem. Phys., 16(6), 3683-3710, doi:10.5194/acp-16-3683-2016, 2016.

Miller, S. M., Wofsy, S. C., Michalak, A. M., Kort, E. A., Andrews, A. E., Biraud, S. C., Dlugokencky, E. J., Eluszkiewicz, J., Fischer, M. L., Janssens-Maenhout, G., Miller, B. R., Miller, J. B., Montzka, S. A., Nehrkorn, T., and Sweeney, C.: Anthropogenic emissions of methane in the United States, P. Natl. Acad. Sci., 110, 20018–20022, doi:10.1073/pnas.1314392110, 2013.

Parker, R., Product User Guide Version 4 (PUGv4) for the Proxy-XCH_4 GOSAT product from the University of Leicester, https://www.leos.le.ac.uk/data/GHG/GOSAT/v7.2/PUGv4_GHG-CCI_CH4_GOS_OCPR.pdf, 2016.

Rödenbeck, C., Gerbig, C., Trusilova, K., and Heimann, M.: A twostep scheme for high-resolution regional atmospheric trace gas inversions based on independent models, Atmos. Chem. Phys., 9, 5331–5342, https://doi.org/10.5194/acp-9-5331-2009, 2009.

Summary of plans for the continuation of the project

(10 lines max)

The global CH_4 flux inversions will be further extended (until 2018) in order to further analyse trends in global and regional CH_4 emissions.

A 2nd series of VERIFY inversions will be performed in the second half of 2018 using updated a priori emission inventories and extended observational data sets. The new inversion series will analyse the use of more consistent observational data set over certain sub-periods (with more complete data coverage) to allow also a better analysis of emission trends.

The coupled FLEXPART-COSMO / TM5 4DVAR inversion system will be further developed. Specific issues for the further development are the speed-up of the current prototype system (which is relatively slow due to the very high spatial resolution), the extension of observational data sets from multiple stations and the investigating of different approaches to estimate the model representation errors.

Figures

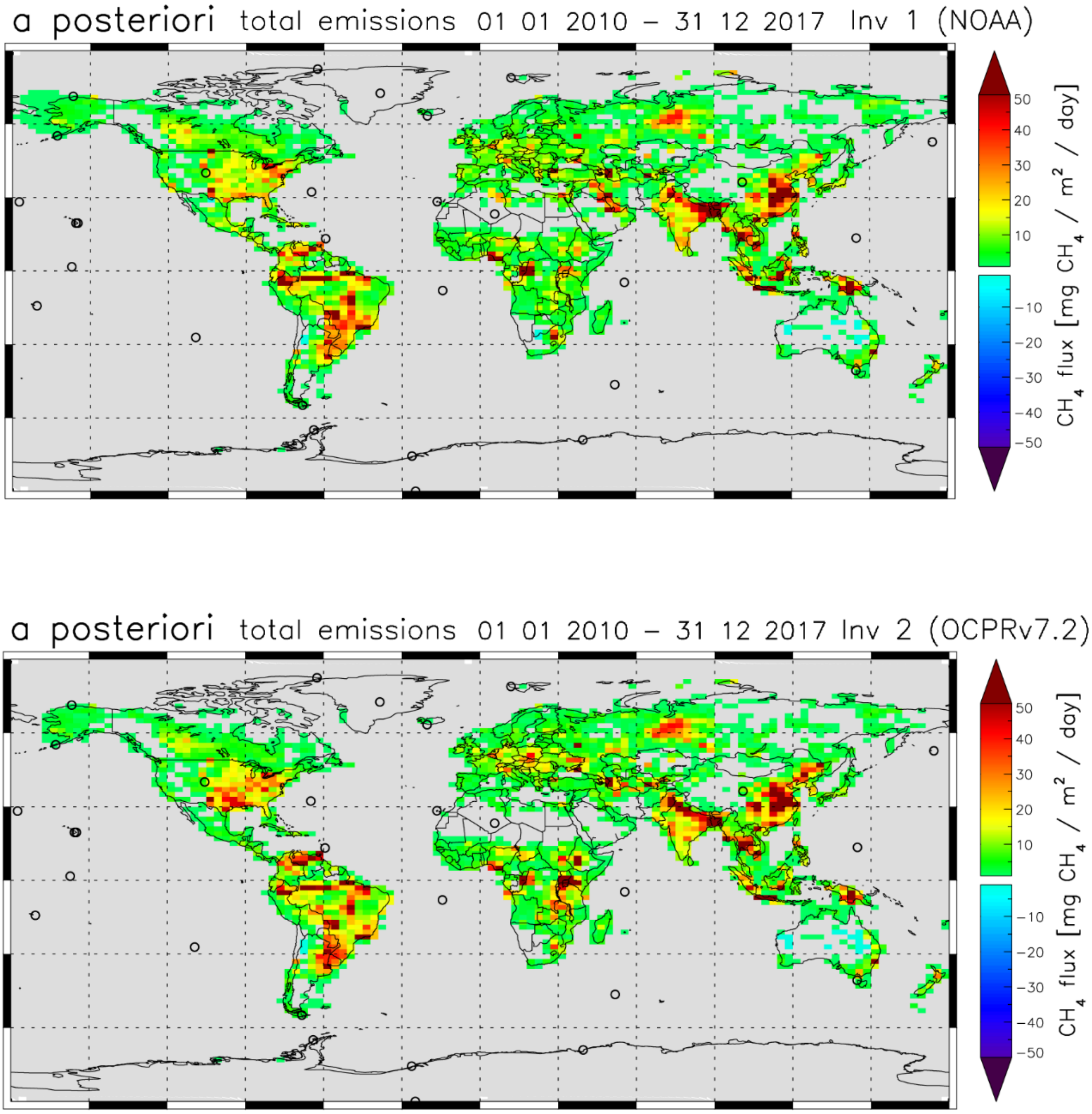

Figure 1: Derived (a posteriori) total CH_4 emissions (average 2010-2017). Top: inversion 'Inv1 (NOAA)' including only NOAA surface observations. Bottom: inversion 'Inv2 (OCPR)' using both NOAA surface observations and XCH_4 satellite retrievals from GOSAT.

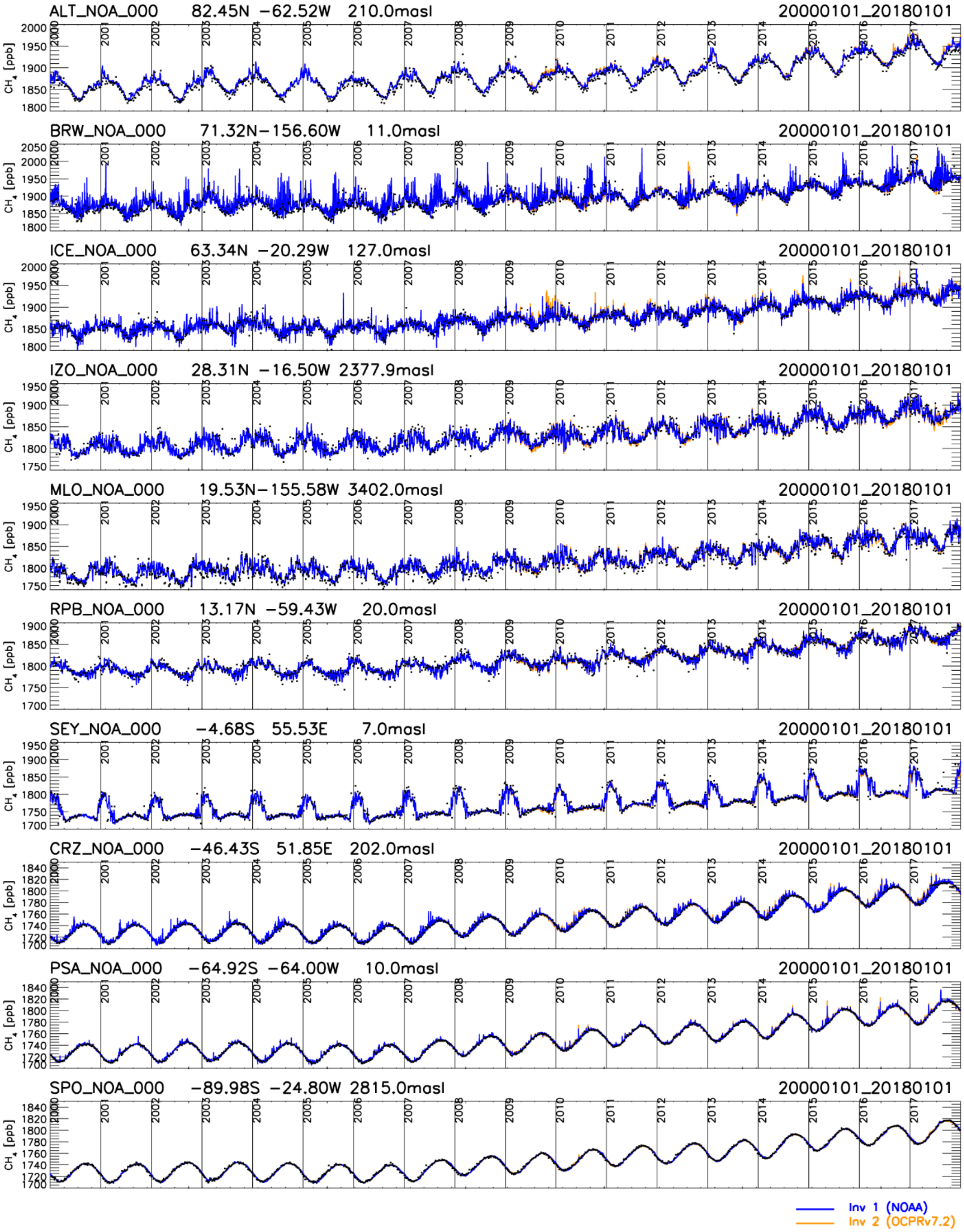

Figure 2: Simulated and observed CH_4 dry air mole fractions at remote global NOAA monitoring stations. Simulations of Inv 2 (OCPRv7.2) for period 2009-2017 (shown in orange) are very similar to simulations of Inv 1 (NOAA) (shown in blue; performed for entire period 2000-2017) and therefore mostly 'hidden' in the figure. Measurements are shown by black symbols.

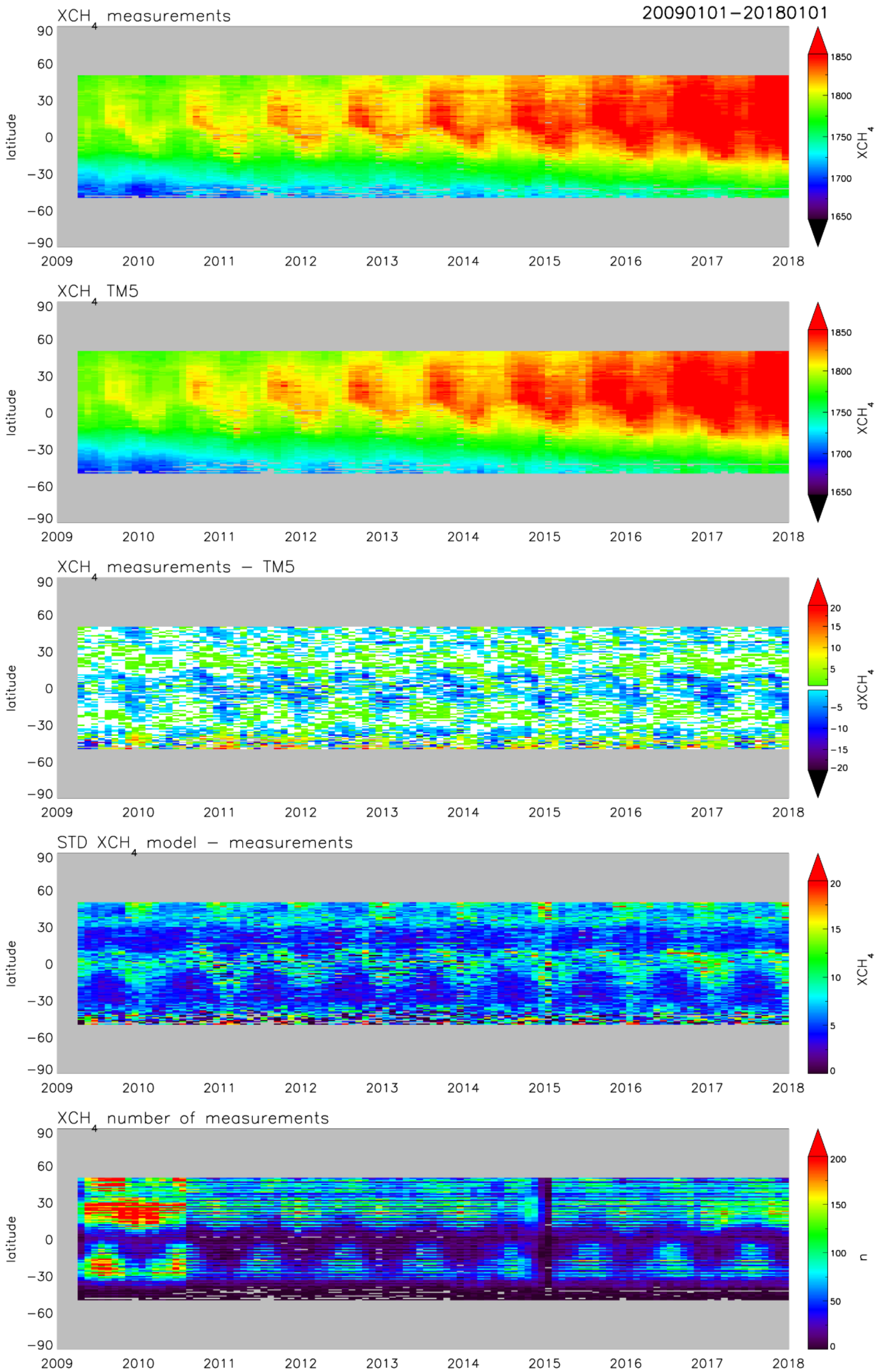

Figure 3: Use of XCH_4 retrievals from GOSAT in inversion 'Inv2 (OCPR)'. Top: XCH_4 retrievals (GOSAT OCPRv7.2 product); latitudinal average. 2nd panel: Assimilated column average dry air mole fractions XCH_4.; latitudinal average; 3rd panel: difference between XCH_4 retrievals and assimilated XCH_4; latitudinal average. 4th panel: standard deviation between XCH_4 retrievals and assimilated XCH_4; 5th panel: total number of used XCH_4 retrievals per latitude.

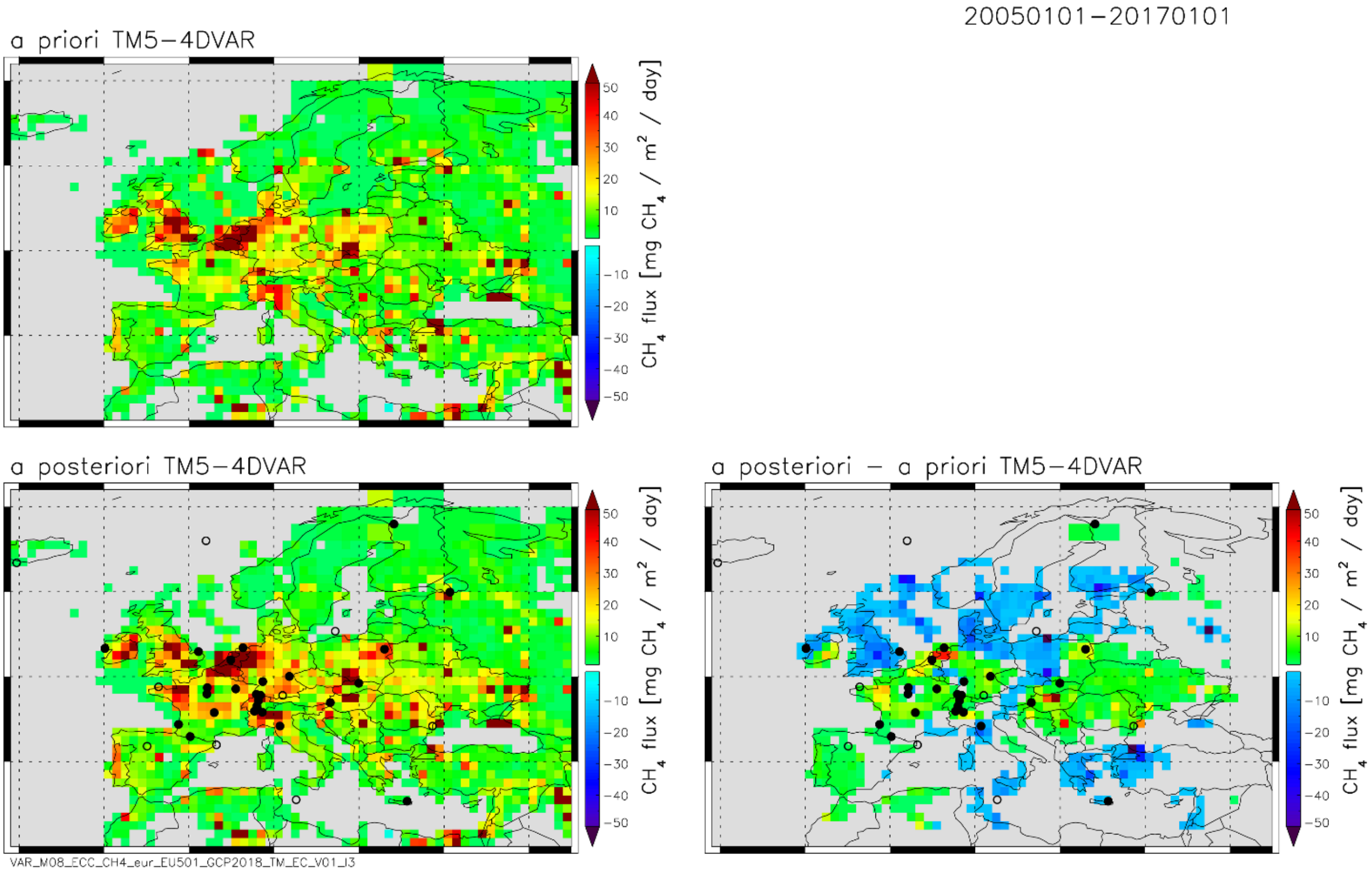

Figure 4: European CH_4 emissions (average 2005-2016). Top left: a priori emissions. Bottom left: a posteriori emissions. Bottom right: difference between a posteriori and a priori.

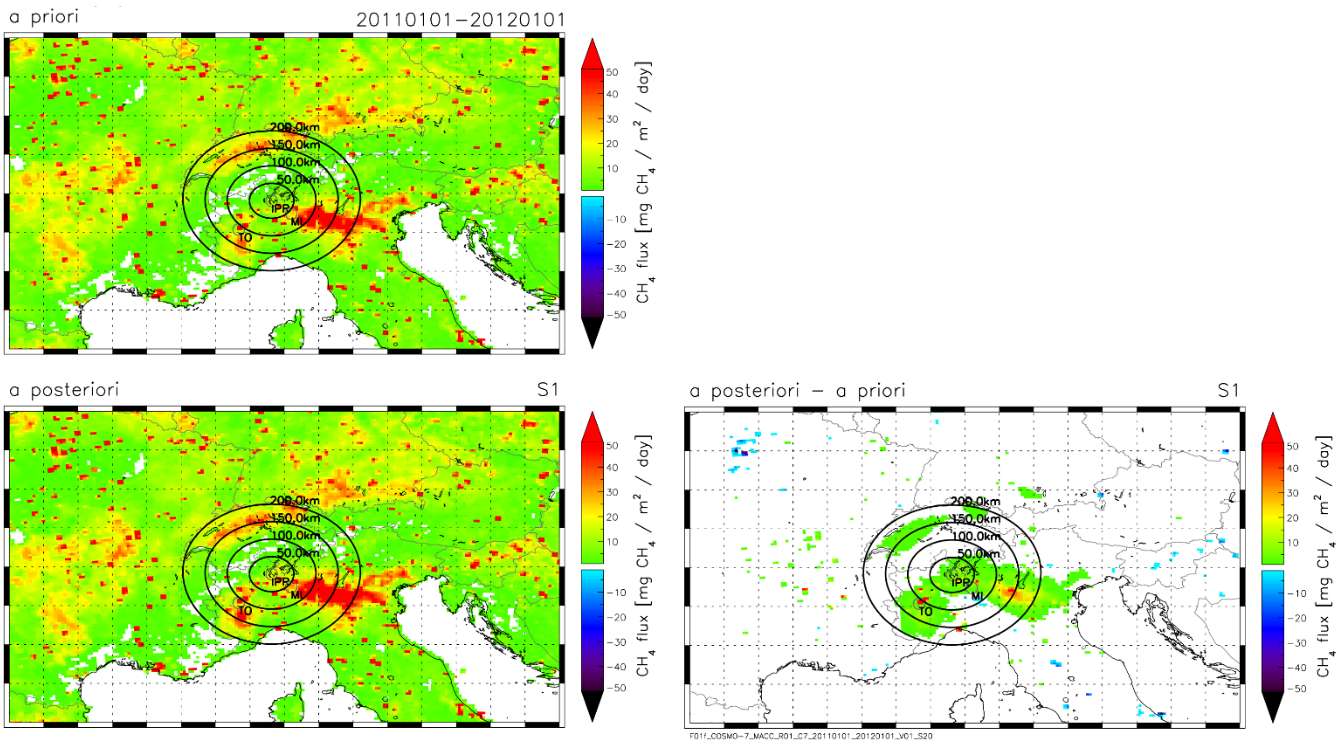

Figure 5: Inverse modelling of regional CH_4 emissions around monitoring station Ispra, Italy using the coupled high-resolution FLEXPART-COSMO-7 / TM5-4DVAR inverse modelling system. Top left: a priori emissions. Bottom left: a posteriori emissions. Bottom right: difference between a posteriori and a priori.