SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Extend and improve CH4 flux inversions at global and European scale based on ERA5 reanalyses
Computer Project Account:	ECJRC
Start Year - End Year :	2022… - 2024
Principal Investigator(s)	Francesco Graziosi
Affiliation/Address:	European Commission, Joint Research Centre (EC-JRC) Directorate for Energy, Mobility and Climate Clean Air and Climate Unit
Other Researchers (Name/Affiliation):	Giovanni Manca; European Commission, Joint Research Centre (EC-JRC) Directorate for Energy, Mobility and Climate Clean Air and Climate Unit

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

Extend and improve estimates of global methane (CH4) emissions. Assess the global methane emissions applying global inversion system (TM5-4DVAR). The purpose of the special project was improving the understanding of the CH_4 source and sink processes investigating CH_4 fluxes trough atmospheric model inversion system. To do this, we calculate the global CH_4 fluxes using TM5-4DVAR inversion system over the period from 2018 to 2021. The inversions were driven by both, surface-based and space born observations. The atmospheric inversion system adopted in this study allows to determine the monthly fluxes from 4 different emission categories: rice fields, wetlands, biomass-burning and anthropogenic sources.

……

Summary of problems encountered

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

No major technical problems encountered

……

……

Experience with the Special Project framework

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

My experience with the administrative aspects of the Special Project framework, including the application procedure and progress reporting, was smooth and satisfactory.

……

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.)

……

The aim of the project was to retrieve global methane (CH_4) fluxes using atmospheric inversion system.
To do this we performed TM5-4DVAR inversion model system developed at European Commission's Joint Research Centre (JRC) [Bergamaschi et al., 2013; Meirink et al., 2008; Segers and Houweling, 2017a; 2017b], which is based on atmospheric chemical transport model called TM5-MP, and its adjoint and uses a 4DVAR variational technique that iteratively minimises the cost function. The inversion model cascade adopted in this study is similar to the one described and used to calculate the Copernicus Atmosphere Monitoring Service (CAMS) re-analysis of methane fluxes and concentration operated by Netherlands Organization for Applied Scientific Research (TNO) and Netherlands Institute for Space Research (SRON).
Brievly, the chemical transport model TM5-MP [Krol et al., 2005] was driven by ECMWF ERA5 meteorological fields.

The original horizontal resolution of the data is 30 km, which is processed into input files at a 1° x 1° latitude-longitude resolution and then adjusted to the model's coarser resolution. The vertical resolution of the meteorological data consists of 137 vertical levels, which are re-gridded to match the model's resolution of 34 layers. The model utilizes surface data at an hourly frequency and 3D fields at a three-hourly frequency to run simulations. To construct to a priori emission fields, monthly mean CH_4 emissions from EDGARv7.0 is used for anthropogenic emissions included in "other sources", while GFAS inventory is used for biomass burning [Kaiser et al., 2012]), EDGARv7.0 for rice, and LPJ-wsl for wetlands [Zhang et al., 2018] . Monthly means of sink tracers, utilizing the parameterization of Lawrence et al. (2001), are adopted to simulate the atmospheric consumption of CH_4.
The model generates the 3D CH_4 mole fraction fields taking in to account the a priori information on emission from wetlands, rice fields, biomass burning and anthropogenic sources, and atmospheric sinks in the troposphere (reacting with OH) and in the stratosphere (OH, CL and O1(D)).

The inversion system ingests the surface based measurements and satellite retrievals as observational constraints to optimise fluxes in the grid cells taking into account the four source categories. The inversion procedure consists of two inversion steps. As the first step, we performed an yearly inversions (including 6-months of spin up and 6 months of spin down) at coarse resolution (6° x 4° latitude longitude and 25 vertical levels) using surface based measurements from NOAA Earth System Research Laboratory (ESRL) [Segers and Houweling, 2017a; 2017b], covering the period from 2018 to 2021, extending one year from the previous report.
This first inversion stream generates the 3D optimized methane mole fraction fields, ingested as initial concentration fields by the second iteration inversions.
The second step consists in a yearly (plus 6 months of spin-up and 6 months of spin-down) high resolution (3° x 2° lat lon and 34 vertical layer) inversion runs covering all the investigated period. We performed two different high resolution inversion streams, 1) using surface based measurements from NOAA only (named S1), and 2) adopting satellite retrievals (from GOSAT satellite) and surface based measurements from NOAA (named S2). For the last high resolution inversion stream (S2), a bias correction was applied.

During the last year of activity, we refined the bias correction system, increasing the time resolution of the bias correction fields applied in the inversions, improving the accuracy of the inversion results. Furthermore, we increased the model sensitivity, adding non-remote sites observations to the measurement network adopted in the inversion cascade. Moreover, measurement sites in the northern high-altitude wetland areas were added to better constrain the CH4 emissions in this region, which were poorly constrained by previous observations network.

However, in order to avoid local contaminations, not reproduced by the model, we selected the measurements ingested by inversion system. Indeed, for the stations with in situ measurements in the boundary layer, the model assimilated measurements in the early afternoon (between 12:00 and 15:00 LT) and for mountain stations only nighttime measurements were assimilated (between 00:00 and 03:00 LT), in similar manner of Bergamaschi et al., [2015].
In addition to the previous report, the inversions at high resolution are conducted using surface-based measurements and the Copernicus Sentinel-5 Precursor satellite using the Tropospheric Monitoring Instrument TROPOMI observations over the global domain were extended to two years. To do this, the TROPOMI observations are post processed into 1° x 1° latitude longitude horizontal resolution super-observations.

Currently we are seeking on quantify the response of methane emissions to climate variables, focusing on wetland emissions, and their sensitivity to climate variables. The significant uncertainties in estimating CH4 emissions

from wetland ecosystems, which are the primary natural source of methane to the atmosphere, greatly impede the accurate quantification of the global methane budget. The production of methane in wetlands is due to microbial methanogenesis, which depends on temperature, water-table depth, and both the quality and quantity of organic matter. Climate change is expected to affect these three main drivers of methanogenesis.
To do this, we analysed the emission response to 2 m temperature (T) and total precipitation (P) based on ECMWF-ERA5 reanalysis. We considered four climate zones based on the Köppen-Geiger classification: boreal, temperate, equatorial, and arid, as showed by fig1.

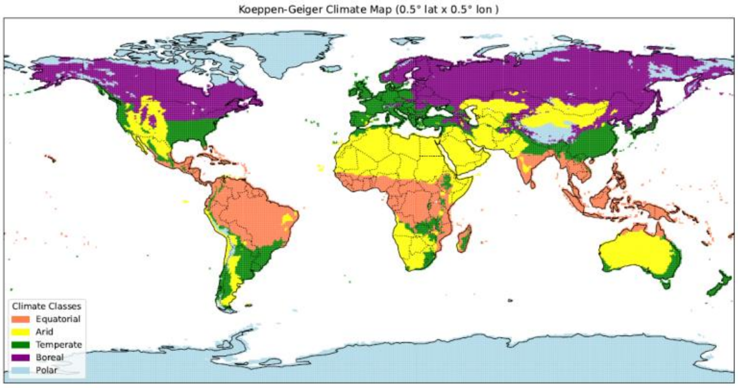

Fig 1 reports the wetland distribution based on Köppen-Geiger classification.

The methane emission distribution over the 4 areas are reported in fig2.

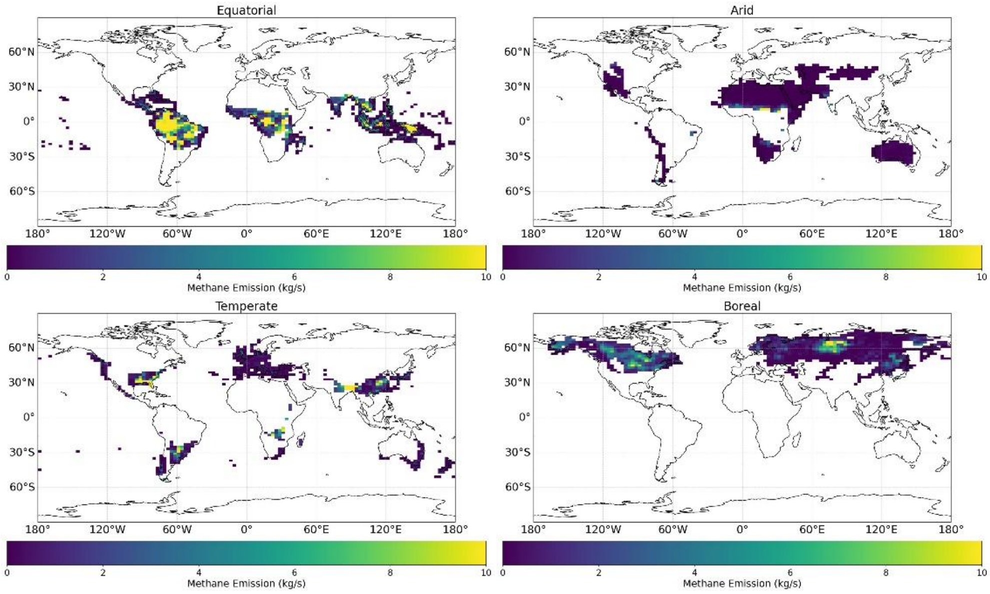

Fig2 Global methane wetland emission distributions across four climate areas.

The total CH_4 wetland emissions, based on inversion analysis, are on average 188 Tg/yr, with the larger part (~60%) originated from tropical regions. Scatterplots reveal the distinct climate sensitivity of wetland emissions across different climatic zones, as reported in fig3.

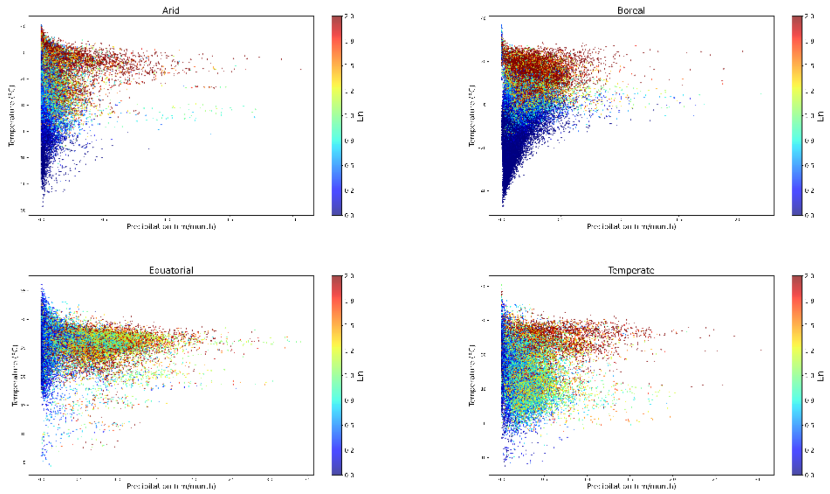

Fig3 Bidimensional Response of Wetland CH_4 Emissions to Temperature (T) and Total Precipitation (P) Across Four Climate Areas.

Consistent with findings by Koffi et al. (2020), cold regions show a strong sensitivity to temperature, indicated by the prominent red distribution in the upper sections of the scatterplots. Conversely, warmer regions, such as the tropics, exhibit greater sensitivity to precipitation. The integrated emission over the boreal and temperate regions, contributing 35 % of the overall wetland emissions, demonstrate a nearly linear relationship with both temperature and precipitation. These regions are expected to expand under future climate scenarios. Consequently, future trends in wetland CH_4 emissions will be influenced by changes in climate. Thus, advancing our scientific understanding of wetland emissions' responses to these climatic variables is crucial for improving predictive models and informing mitigation strategies within the context of global climate change.

References

Bergamaschi, P., S. Houweling, A. Segers, M. Krol, C. Frankenberg, R. A. Scheepmaker, E. Dlugokencky, S. C. Wofsy, E. A. Kort, C. Sweeney, T. Schuck, C. Brenninkmeijer, H. Chen, V. Beck, and C. Gerbig, Atmospheric CH4 in the first decade of the 21st century: Inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements, J. Geophys. Res.-Atmos., 118(13), 7350-7369, doi:10.1002/jgrd.50480, 2013.

Bergamaschi, P., Corazza, M., Karstens, U., Athanassiadou, M., Thompson, R. L., Pison, I., Manning, A. J., Bousquet, P., Segers, A., Vermeulen, A. T., Janssens-Maenhout, G., Schmidt, M., Ramonet, M., Meinhardt, F., Aalto, T., Haszpra, L., Moncrieff, J., Popa, M. E., Lowry, D., Steinbacher, M., Jordan, A., O'Doherty, S., Piacentino, S., and Dlugokencky, E.: Top-down estimates of European CH4 and N2O emissions based on four different inverse models, Atmos. Chem. Phys., 15, 715–736, https://doi.org/10.5194/acp-15-715-2015, 2015.

Koffi Ernest N. *et al.*,An observation-constrained assessment of the climate sensitivity and future trajectories of wetland methane emissions.*Sci.Adv.*6,eaay4444(2020).DOI:10.1126/sciadv.aay4444

Krol, M., S. Houweling, B. Bregman, M. van den Broek, A. Segers, P. van Velthoven, W. Peters, F. Dentener, and P. Bergamaschi, The two-way nested global chemistry-transport zoom model TM5: algorithm and applications, Atmos. Chem. Phys., 5, 417-432, doi:10.5194/acp-5-417-2005, 2005.

Meirink, J. F., P. Bergamaschi, and M. Krol, Four-dimensional variational data assimilation for inverse modelling of atmospheric methane emissions: Method and comparison with 50 synthesis inversion, Atmos. Chem. Phys. , 8, 6341–6353, doi:10.5194/acp-8-6341-2008, 2008.

Segers , A., and S. Houweling, Description of the CH4 Inversion Production Chain, https://atmosphere.copernicus.eu/sites/default/files/FileRepository/Resources/Validationreports/Fluxes/CAMS73_2015SC2_D73.2.5.5-2017_201712_production_chain_v1.pdf, 2017a.

Segers, A., and S. Houweling, Validation of the CH4 surface flux inversion - reanalysis 2000-2016, CAMS73_2015SC2_D73.2.4.4-2016_201712_validation_CH4_2000-2016_v1, 2017b.

……………………………………………………………………………………………

List of publications/reports from the project with complete references

Graziosi et al., 2025 Inverse modelling of global CH_4 emissions using surface-based measurements and GOSAT satellites retrievals; EGU General Assembly, 2025, Hall X1, Vienna, Austria
…………………………………………………………………………………………………

……

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 future plans consists on extend the analysis over more years and analyse the sensitivity of the satellite observations to the wetland emissions areas………………………………………………………………………………………