,
Horizon 2020 Societal challenge 5:
Climate action, environment, resource
efficiency and raw materials

VERIFY

Observation-based system for monitoring and verification of greenhouse gases

GA number 776810, RIA

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Internal reviewer:	Isabelle Pison, Philippe Peylin and Aurélie Paquirissamy

Changes with respect to the DoA
None
Dissemination and uptake
The model results will be made available via the VERIFY project database and are currently available via a data server (in some cases registration will be necessary). These model results are used in the top-down (inverse) modelling approach for D4.7 and will be used in the synthesis product in WP5.
Short Summary of results (<250 words)
Natural CH_4 emissions are an important component of the global CH_4 budget, comprising approximately 40% of the total emissions. The largest source of natural emissions is from wetlands with a smaller, but very uncertain, contribution from inland water bodies. This deliverable provides estimates of natural emissions of CH_4 from wetlands and inland water bodies, as well as fluxes to/from mineral soils. Two modelling frameworks are used to estimate the emissions: 1) the combined model JSBACH-HIMMELI, which is used to estimate wetland and mineral soil emissions, and 2) an empirical model of inland water emissions. JSBACH-HIMMELI is a process-based model consisting of a land-surface model, JSBACH, which is used to drive a model of CH_4 emissions from wetlands, HIMMELI (see Section 4.1.1). The inland water bodies model is empirical and scales-up measurements of CH_4 emissions from lakes and reservoirs to the European scale relying on proxy data (see Section 4.1.2). Results are presented from both models as gridded maps at 0.1°×0.1° resolution for Europe (see Section 4.2).
Evidence of accomplishment
All the simulation results will be accessible through the dedicated data THREDDS server. Note that some of these data may be password protected during a consolidation phase and thus only accessible to the VERIFY partners (accessible through the internal share-point platform).

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Version	Date	Description	Author (Organisation)
V0	05/06/20	Creation/Writing	Tiina Markkanen (FMI)
V0.1	18/12/20	Formatting/Delivery	Rona Thompson (NILU)
V1	31/01/2021	Formatting/Delivery on the Participant Portal	Isabelle Pison, Philippe Peylin and Aurélie Paquirissamy (CEA/LSCE)
V2	28/06/2021	Revised version after reviewers comments	Pierre Regnier (ULB)

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1. Glossary

Abbreviation / Acronym	Description/meaning
JSBACH	The land surface model of MPI-ESM
HIMMELI	The methane production and transport model of UHel and FMI
CLC	The CORINE land cover data of Copernicus
HydroLAKES	The global lake shoreline polygon database
CSLM	The bulk mixed-layer thermodynamic Canadian Small Lake Model
MSM	Mechanistic-stochastic-model
ISIMIP	The Inter-Sectoral Impact Model Intercomparison Project for projecting the impacts of climate change
GCP	Global carbon project
NUTS 2016	The nomenclature of territorial units for statistics

2. Executive Summary

This report gives an overview of the model set-ups used to produce natural methane balance estimates including terrestrial areas and inland water bodies. The CH_4 emission/sink data specified here are follow up to respective deliverables last year and thus this report, in addition to the basic description of the modeling tools, details the changes made to the model framework between the first and the second deliverable. The report contains summary statistics of European level yearly balances to illustrate year to year variability of the estimated quantities as well as maps that show the spatial distributions of time average fluxes. The CH_4 balance estimates are used as prior information for the atmospheric inversion frameworks operated in this work package.

Since the previous deliverable the climatic model drivers were changed and the simulated period was extended to cover year 2018. Minor changes were made on the peatland area distribution that determines the fractional area for which HIMMELI peatland model and a mineral soil approach are applied to estimate the total terrestrial methane balance. Moreover the calculations of mineral soil methane fluxes were revisited and produce now more realistic ranges of emissions and sinks than previously.

Additionally a global CH_4 terrestrial flux product that covers the years 2005-2017 is described. The same approaches as for the European estimate have been used to compose the global CH_4 estimate.

For the next deliverables the flux time series will be extended by one year. For the terrestrial estimates more suitable options for the peatland distribution will be assessed. The CH_4 process model HIMMELI as well as mineral soil flux estimates will be further assessed against observation data. Development of a process model for lakes will be finalized and the first attempts with temporal flux dynamics will be presented. The temporally resolved estimates will make use of the meteorological data GSWP3-W5E5 that are used by the lake-sector of the Intersectorial Impact Model Intercomparison Project (ISIMIP), hence ensuring consistency with their ongoing activities. In addition, we will provide a simple climatology of river CH4 emissions using the distribution of river surface area over Europe (same distribution as for the CO2 emissions, WP3) and a mean estimate and range based on a recent compilation performed by RECCAP2. The latter compilation will also be used to compare our modelled lake CH4 emissions with estimates derived from observations, in addition to the assessment already performed in this deliverable (see below). The rationale for focusing on lakes in VERIFY was based on an initial assessment of CH4 emissions for all inland water bodies, for which we found that rivers are relatively minor contributors to the overall emissions. The latest synthesis from RECCAP2 confirms this earlier finding.

3. Introduction

This document describes the two modelling frameworks used to estimate natural emissions of CH_4. Natural emissions of CH_4 are primarily those from peatlands (and to a lesser extent mineral soils) and fresh water systems. While there is also a natural geological source of CH_4, this is not covered in VERIFY, and estimates for this source vary widely, from nearly negligible with a global total of 1-5 Tg/y to significant with a global total of approximately 50 Tg/y. The model framework, JSBACH-HIMMELI is used to estimate peatland and mineral soil emissions, and an empirical model is used to estimate the emissions from inland water bodies.

4. Natural fluxes of methane

4.1. Model descriptions

4.1.1. Peatland and mineral soil fluxes

JSBACH-HIMMELI is a combination of two models, JSBACH, which is a land-surface model, and HIMMELI, which is a specific model for northern wetland emissions of CH_4. HIMMELI (HelsinkI Model of MEthane buiLd-up and emIssion for peatlands) has been developed especially for estimating CH_4 production and transport in northern peatlands and simulates both CH_4 and CO_2 fluxes in peatlands and can be easily used as a module within different modelling environments (Raivonen et al., 2017, Susiluoto et al., 2018). HIMMELI is driven with soil temperature, water table depth, the leaf area index and anoxic respiration. These parameters are provided to HIMMELI from the land surface model, JSBACH, which models hydrology, vegetation and soil carbon input (Reick et al 2013). A soil thermal model with coupling of hydrology through melting and freezing (Ekici et al. 2014) is used in the set-up for D4.5 (which was not used in D4.4). Linked to the coupled thermal and hydrology, dynamic snow properties are applied. Moreover, the EU-CORINE land cover data conversion to JSBACH plant functional types is slightly modified so that only “bogs” and “inland marshes” are interpreted as wetlands, which correspond closest to the high-emitting pristine wetland category and better harmonize with the land uses in a higher level of EU-Corine for this task. In the previous data product 50% of “moors and heathlands” were additionally included. Land covered by all the other CORINE land cover types are considered and treated as mineral soil for CH_4 uptake and emission to include the small but spatially extensive methane fluxes otherwise neglected. CH_4 emission and uptake of mineral soils are calculated following the method by Spahni et al. (2011). Soil moisture, soil temperature and soil heterotrophic respiration control CH_4 emission and uptake in the model. Wetland emissions are finally corrected to account for the wetland distribution. Climate drivers for the European model set-up were obtained from the project and were same as those used in WP3.

In addition to the European emission deliverable described in the project plan, we prepared a global emission product. This was an addition by request of inversion modelers, and was not included in the project work plan. Thus the global emission product is not produced as a common effort in the project or harmonized with other WPs. Also, we did not use climate drivers provided by the project because the project climate drivers were prepared, as originally planned, only for Europe for purposes of reaching high spatial resolution. In the global set-up the land cover and climate drivers over Europe are based on global data sources and thus the global set-up should be considered as completely separate from the European, both forming their own internally consistent systems. In the global set-up, we used the native land cover distribution of the JSBACH model in 1.875° resolution. In the set-up the fraction of Histosols in the Harmonised World Soil Database (HWSD) were identified as the fractional peatland cover north of 45°N. Moreover, a negligible fraction of peatland was attributed to all the grid cells and the modeled methane flux for that fraction can be scaled to produce a regional estimate with any preferred peatland fraction. In the global set-up the methane emissions of inundated areas south of 45°N were calculated following the formulation by Spahni et al (2011) and the inundated fraction was adopted from the set-up applied in global carbon project (GCP, Saunois et al, 2020). The CRUJRA climate drivers were adopted from GCP as well. The methane flux estimates were processed for years 2005-2017.

4.1.2. Inland water bodies

This data set represents two climatologies of average annual CH_4 emissions (sum of diffusive and ebullitive emissions) from lakes and reservoirs at the spatial resolution of 0.1°. The alternative estimates are based on the HydroLAKES database (Messager et al., 2016).

The first climatology is based on direct upscaling from observed CH_4 emission rates which includes local measurements in 155 lakes and reservoirs, spread over Europe, and which we have classified into rates reported for small lakes (<0.3 km^2), larger (>0.3 km^2) lakes, and reservoirs. In addition, we applied a coarse regionalization distinguishing the Boreal (>54°N) from the Temperate to Sub-Tropical (<54°N) zone. The second climatology is based on a modelling approach, which predicts CH_4 emission rates from nutrient (phosphorous and nitrogen) concentrations in lakes and reservoirs (Stavert et al., in rev. for GCB). This model uses simulated nutrient concentrations taken from the studies of Maavara et al. (2019) and Lauerwald et al. (2019), and a set of empirical equations predicting chlorophyll-a concentrations from nutrient concentrations (McCauley et al., 1989) and relating CH_4 emission to chlorophyll-a concentrations (Deemer et al., 2016; DelSontro et al., 2018). A Monte-Carlo analysis was used to propagate the uncertainty from the empirical equations used in that model to the final CH4 emission estimate. We present the median of the Monte-Carlo results as best estimate, and the 5th and 95th percentile as lower and upper bound.

The above approaches provide a climatology of mean annual CH_4 emissions from European lakes from observations. An important limitation is thus the lack of temporal resolution (both seasonal and interannual). To circumvent this limitation, the development of a process-based CH_4 emission model has been initiated over the last few months. This model has been embedded in the one-dimensional bulk mixed-layer thermodynamic Canadian Small Lake Model (CSLM; MacKay, 2012), and was used to determine the ebullition and diffusion fluxes as well as CH_4 concentrations. The application of the model to simulate some European lakes shows promising results (See section 4.2.5 Figure 4). The model is currently under development to simulate lakes in a regional/global scale with the minimum number of inputs and lakes characteristics that might not be readily available. Our model developments also takes advantage of forcings and physical model outputs provided by the ISIMIP lake sector initiative (collaboration with Prof. W. Thiery, VUB, Belgium).

4.2. Results

4.2.1. Peatland and mineral soil fluxes

Simulations using JSBACH-HIMMELI for peatland and mineral soil fluxes of CH_4 have been completed for Europe at 0.1°×0.1° covering the period 2000-2018. An overview of mean annual

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European methane fluxes is given in Table 1 for year 2005 – 2018. Mineral soil fluxes are a net flux, sum of wet soil emission and dry soil uptake, calculated following approach by Spahni et al., (2011) and utilising soil moisture, temperature and soil respiration input from JSBACH model. The uncertainty of the European natural methane emissions is very large. The uncertainty of mineral soil fluxes is estimated by model sensitivity tests to be from -50% to 15%. Even though the estimated peatland fluxes generally agree with the local flux measurements a conservative uncertainty estimate of +-80% is given because of a high variability of the observational data, sparseness of the observation network and uncertainty of peatland spatial distribution.

Year	Peatland flux	Mineral soil flux (negative is uptake)
2005	2.195	-1.254
2006	2.257	-1.243
2007	2.138	-1.293
2008	2.048	-1.266
2009	2.146	-1.223
2010	2.201	-1.202
2011	2.316	-1.274
2012	2.057	-1.230
2013	2.425	-1.258
2014	2.448	-1.310
2015	2.103	-1.343
2016	2.244	-1.266
2017	2.131	-1.243
2018	2.450	-1.309

Table 1: Methane emissions (positive) and uptake (negative) from JSBACH-HIMMELI in Tg(CH_4)/yr for an area of 35.0°N to 73°N and 12°W to 37.8°E. Mineral soil flux is the total of dry soil uptake and wet soil emission.

4.2.2. Peatlands

The European peatland methane fluxes are mapped in Figure 1. The distribution of the emissions follows the peatland map newly created based on the EU-CORINE land use map with national specifications and information on river and lake distributions. The magnitude of the emissions is sensitive to e.g. simulated peat water table depth, temperature profile and dynamically changing fresh substrate input from peatland vegetation.

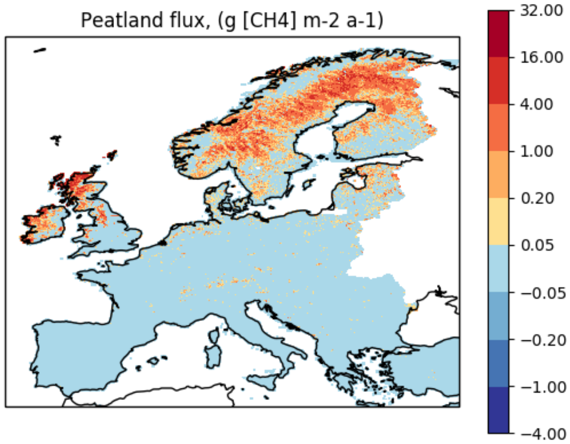

Figure 1 : Peatland emissions from JSBACH-HIMMELI within the area of CORINE land cover data coverage. Average over years 2005 – 2018

4.2.3. Mineral soils

The European mineral soil methane fluxes are mapped in Figure 2, showing the net flux of the wet mineral soil emissions and dry mineral soil uptake. Soil moisture is an important factor regulating the fluxes since the model simulates emission only when a certain soil moisture threshold, 95% of water holding capacity, is exceeded. Already as such soil moisture is challenging to simulate, and adding that there is limited information on the moisture level where the soil turns from methane sink to methane source, the total mineral land methane fluxes are very uncertain. In the current simulations the wet mineral soil methane emissions were closely connected to precipitation events and the magnitude of the emission was large during the events. Dry soil sink was more evenly distributed with larger sink in the south.

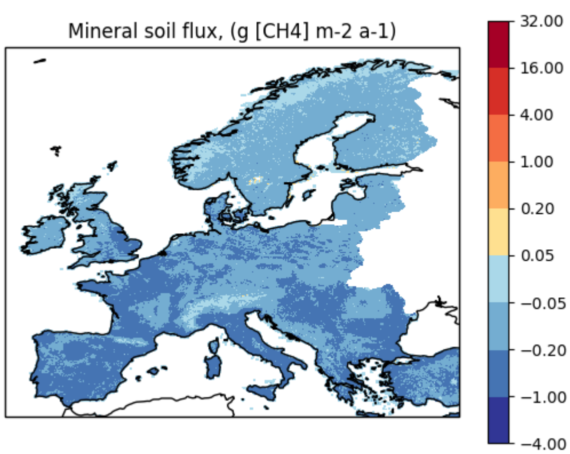

Figure 2 : Mineral soil fluxes from JSBACH-HIMMELI (g m-2 a-1). Average over years 2005-2018

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4.2.4. Global wetland methane fluxes

Our global simulation of CH_4 fluxes (totaling 133 Tg [CH_4]/yr, with: Peat 20 Tg/yr, Mineral soil emission 121 Tg/yr, Mineral soil uptake -44 Tg/yr and Inundated soil 36 Tg/yr) compares well with GCP estimates ranging from 102 to 182 Tg [CH_4]/yr. Figure 3 shows mean yearly balance through years 2005-2017.

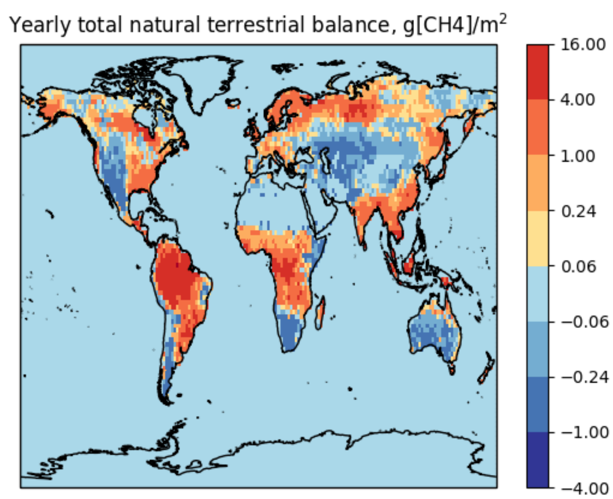


Figure 3: Peatland emissions from JSBACH-HIMMELI within the area of CORINE land cover data coverage. Average over years 2005 – 2018.

4.2.5. Inland water bodies

Our observation-based climatology (Fig. 4, left) and model results (Fig. 4, right) give the average annual CH_4 emission from lakes (including reservoirs) for the period 1990 to the present day. For the area covered by the NUTS 2016 regions (EU membership countries, + EU candidates and EFTA countries), we estimate an annual emission of 0.8 Tg CH4-C yr-1 from the data-driven assessment (confidence interval to be provided in D4.6) and of 2.3 (1.0-5.1, 5th and 95th percentile of confidence interval) Tg CH4-C yr-1 for the model results. Note that the two climatologies were merged in the European CH4 budget synthesis of Petrescu et al. (2021), thereby further accounting for the uncertainties in inland water CH4 emissions. In both cases, the spatial pattern is dominated by the lake surface area distribution, with Finland and Scandinavia being hotspot regions. Nevertheless, other factors come also into play, in particular the control of CH4 emissions by the lake trophic status. This control was already identified in the data-driven approach (see, e.g. Rinta et al. 2017), and is well captured by our model, the mechanistic-stochastic-modeling (MSM) approach of Maavara et al. (2019) accounting for the nutrient loads delivered from the catchment to each lake of the European domain.

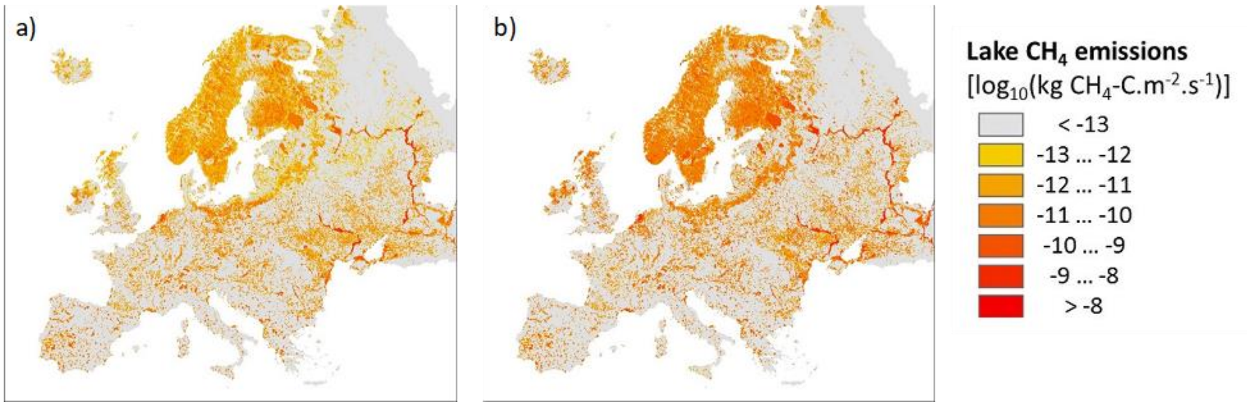
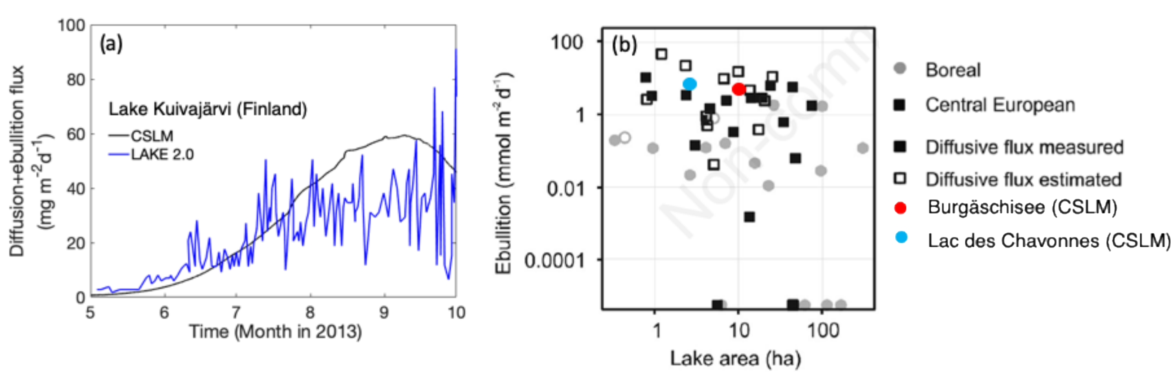


Figure 4 : Estimated CH4 emission from lakes and reservoirs derived from a) observations and b) model simulations Flux rates refer to total continental area.

To resolve the temporal evolution of CH4 emissions we expanded the biogeochemical module of the MSM to resolve the seasonal dynamics and the biogeochemical processes of the CH4 and O2 cycles occurring in the water column and sediments This module was then coupled to CSLM to constrain the lake physics, leading to CSLM-CH4. For carbon, the model simulates a lake-mean trophic state from the balance between Net Primary Production (NPP) and heterotrophic decomposition. It then simulates profiles of oxygen and CH4 by accounting for vertical transport and the set of consumption/production processes of the O2-CH4 cycles. In the sediment, CH4 production accounts for shallow water production, and separates the diffusive and ebullitive pathways using an approach modified from Langenegger et al., 2019. Overall, this approach allows to constrain the seasonal distribution (Fig. 5a) and spatial distribution (Fig. 5b) of CH4 fluxes according to climate conditions (local forcings or ISIMIP-lake sector meteorological data), lake depth, and lake trophic status (controlled by catchment N & P loadings). Figs. 5c-e show that the CSLM-CH4 can also reproduce broad trends in NPP, organic carbon concentration, and CH4 fluxes from lakes reported in the literature.



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c

	Ultra-Oligo	Oligo	Meso	Eutro
Mean PP** ($g\ C\ m^{-2}\ y^{-1}$)	50	50-300	250-1000	> 1000
Mean PP ($g\ C\ m^{-2}\ y^{-1}$)	103-139	206-276	410-547	613-813
TOC** ($mg\ C\ l^{-1}$)	< 1	1-3	<5	5-30
OC ($mg\ C\ l^{-1}$)	0.6-1.6	1.3-3.2	2.6-6.4	3.9-10
F_{CH4} (ebullitive)*	0	3-8	16 - 35	31-60
F_{CH4} (diffusive)*	0	1-8	9 - 35	18-61
F_{CH4} (total, $mg\ CH_4\ m^{-2}\ d^{-1}$)	0	4-16	25-70	49-121

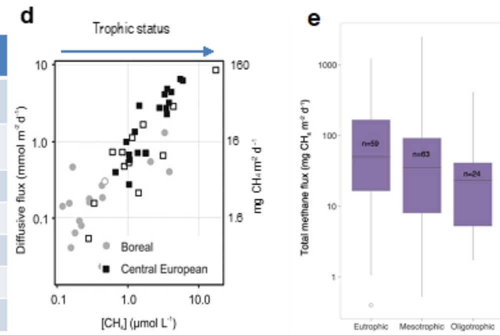

Figure 5: CH4 flux from sediment (diffusion plus ebullition) in Lake Kuivajärvi using LAKE 2.0 model (Stepanenko et al., 2016; blue) and CSLM-CH4 (black), (b) ebullitive flux of CH4 relative to lake area in central European and boreal lakes from measurements (Rinta et al., 2017; black, grey and white symbols) and CSLM_CH4 (Burgäschisee (red) and Lac des Chavonnes (blue)), (c) Comparison of main lake biogeochemical characteristics for a wide range of lake trophic status: CSLM-CH4 in red, data synthesis from Wetzel, 2001 in black, (d) range of CH4 diffusive flux in European lakes from Rinta et al., 2017, (e) range of total CH4 fluxes in global lakes from Rosentreter et al. (2021).

4.3. Planned developments

4.3.1. Peatland and mineral soil fluxes

Over the next year, we will update the fluxes using a new release of high-resolution climate driver data provided by the VERIFY WP3 and extend to year 2020. We will update the EU-CORINE-based land use map to further improve the wetland distribution and further inspect optional land cover data sources. We will develop and improve the calculation of mineral soil fluxes. We will engage multi-site flux measurements and other observations to further develop and calibrate the process model and validate the regional results.

4.3.2. Inland water bodies

Over the next year, we will finalize the development of the process-based model approach and provide first estimates of temporally resolved lake CH4 emissions. The regional upscaling is currently performed by running simulations at the grid cell level, each grid accommodating different lake size classes and nutrient loadings. The model is forced by daily climate forcing at each grid from the ISIMIP lake sector initiative.

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5. Conclusions

Methane balances of terrestrial and inland water systems have been produced using selected process based and regression models. The yearly inland water system methane balance covers the whole Europe since 1990. The two terrestrial methane balance products cover Europe and the globe for years 2005-2018 and 2005-2017, respectively. These two products have been simulated with the same tools but deviate in terms of climatic forcing and boundary data.
The natural methane flux estimates are used as prior data in the atmospheric inversion modeling task of this work package. The applied areal domains as well as time coverages and resolutions may limit the applicability of the products.

For the next deliverables the data series will be extended by one year. The temporal resolution of the inland water balances will be improved. Optional data sources for providing the distribution of northern peatlands simulated with HIMMELI peatland model will be inspected.

6. References

1. Deemer, B. R., Harrison, J. A., Li, S., Beaulieu, J. J., DelSontro, T., Barros, N., Bezerra-Neto, J. F., Powers, S. M., dos Santos, M. A. and Vonk, J. A.: Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis, Bioscience, 66(11), 949–964, doi:10.1093/biosci/biw117, 2016.
2. DelSontro, T., Beaulieu, J. J. and Downing, J. A.: Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change, Limnol. Oceanogr. Lett., 3(3), 64–75, doi:10.1002/lol2.10073, 2018.
3. Ekici, A., Beer, C., Hagemann, S., Boike, J., Langer, M., and Hauck, C.: Simulating high-latitude permafrost regions by the JSBACH terrestrial ecosystem model, Geosci. Model Dev., 7, 631–647, https://doi.org/10.5194/gmd-7-631-2014, 2014.
4. Langenegger, T., et al. What the bubble knows: Lake methane dynamics revealed by sediment gas bubble composition. Limnology and Oceanography 64 (4): 1526–1544, 2019.
5. Lauerwald, R., Regnier, P., Figueiredo, V., Enrich-Prast, A., Bastviken, D., Lehner, B., Maavara, T., Raymond, P.: Natural lakes are a minor global source of N2O to the atmosphere, Global Biogeochemical Cycles, 33, 1564–1581, doi:10.1029/2019GB006261, 2019
6. Maavara, T., Lauerwald, R., Laruelle, G., Akbarzadeh, Z., Bouskill, N., Van Cappellen, P. and Regnier, P.: Nitrous oxide emissions from inland waters: Are IPCC estimates too high?, Glob. Chang. Biol., 25(2), 473–488, doi:10.1111/gcb.14504, 2019.
7. McCauley, E., Downing, J. A. and Watson, S.: Sigmoid Relationships between Nutrients and Chlorophyll among Lakes, Can. J. Fish. Aquat. Sci., 46(7), 1171–1175, doi:10.1139/f89-152, 1989.
8. MacKay, M. D.: A Process-Oriented Small Lake Scheme for Coupled Climate Modeling Applications. Journal of Hydrometeorology, 13(6), 1911–1924. https://doi.org/10.1175/JHM-D-11-0116.1, 2012.
9. Messager, M. L., Lehner, B., Grill, G., Nedeva, I. and Schmitt, O.: Estimating the volume and age of water stored in global lakes using a geo-statistical approach, Nat. Commun., 7, 13603, doi:10.1038/ncomms13603, 2016.
10. Petrescu, A. M. R. et al. The consolidated European synthesis of CH4 and N2O 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
11. Raivonen,M., Smolander, S., Backman, L., Susiluoto, J., Aalto, T., Markkanen, T., Mäkelä, J., Rinne, J., Peltola, O., Aurela, M., Tomasic, M., Li, X., Larmola, T., Juutinen, S., Tuittila, E-S., Heimann, M., Sevanto, S., Kleinen, T., Brovkin, V., and Vesala T.: HIMMELI v1.0: HelsinkI Model of MEthane buiLd-up and emIssion for peatlands, Geosci. Model Devel., 10, 4665-4691, 2017.
12. Reick, C., Raddatz, T., Brovkin, V. & Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM. Journal of Advances in Modeling Earth Systems, 5, 459-482 , https://doi.org/10.1002/jame.20022, 2013.
13. Rinta P, Bastviken D, Schilder J, Van Hardenbroek M, Stötter T, Heiri O.: Higher late summer methane emission from central than northern European lakes. J Limnol 76:52–67, 2017.
14. 14. Rosentreter, J.A., Borges, A.V., Deemer, B.R. et al. Half of global methane emissions come from highly variable aquatic ecosystem sources. Nat. Geosci. 14, 225–230, https://doi.org/10.1038/s41561-021-00715-2, 2021.
15. Saunois et al. The Global Methane Budget 2000–2017, Earth System Science Data, 12(3), 1561–1623, doi:https://doi.org/10.5194/essd-12-1561-2020, 2020
16. Spahni, R., Wania, R., Neef, L., van Weele, M., Pison, I., Bousquet, P., Frankenberg, C., Foster, P. N., Joos, F., Prentice, I. C., and van Velthoven, P.: Constraining global methane emissions and uptake by ecosystems, Biogeosciences, 8, 1643-1665, https://doi.org/10.5194/bg-8-1643-2011, 2011.
17. Stepanenko, V., Mammarella, I., Ojala, A., Miettinen, H., Lykosov, V., & Vesala, T.: LAKE 2.0: A model for temperature, methane, carbon dioxide and oxygen dynamics in lakes. Geoscientific Model Development, 9(5), 1977–2006. https://doi.org/10.5194/gmd-9-1977-2016, 2016.
18. Susiluoto, J., Raivonen, M., Backman, L., Laine, M., Mäkelä, J., Peltola, O., Vesala, T., and Aalto, T.: Calibrating a wetland methane emission model with hierarchical modeling and adaptive MCMC, Geosci. Model Dev., 11, 1199–1228, https://doi.org/10.5194/gmd-11-1199-2018, 2018
19. Wetzel, R.G. Limnology: Lake and river ecosystems (3rd ed.) Academic Press, San Diego. 2001.

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