The Global Methane Budget: 2000-2020

Saunois et al., ESSD, 2024

Detailed Response to Anonymous Referee #3

We acknowledge the referee for the time spent on reading and commenting on the paper. We thank him for his useful corrections and suggestions on the paper, which have helped to clarify and improve the manuscript. Below are the responses (in black) to his comments (in italics, blue). Changes in the text follow each response in bold font.

This paper provides a comprehensive and transparent set of estimates of the global methane budget, updating previous versions of this living review and dataset. The update incorporates improved wetland and freshwater estimates compared to previous estimates, with reduced double-counting of tin bottom-up budgets. Partly as a result of this, the top-down and bottom-up budget estimates now overlap in terms of their uncertainty, when this was not previously the case. The budget dataset is publicly accessible.
As a potential peripheral user of this dataset (through methane lifetime being affected by atmospheric processes that I study), I had plenty to learn about the methane budget, but feel I provided a thorough check of the whole document and dataset from my perspective. I would be happy to use this dataset and consider the paper a useful reference document. The paper is long, of course, but the authors have done well to keep it readable. I would encourage the introduction of a contents section. I provide a few comments below for the authors to consider and check.

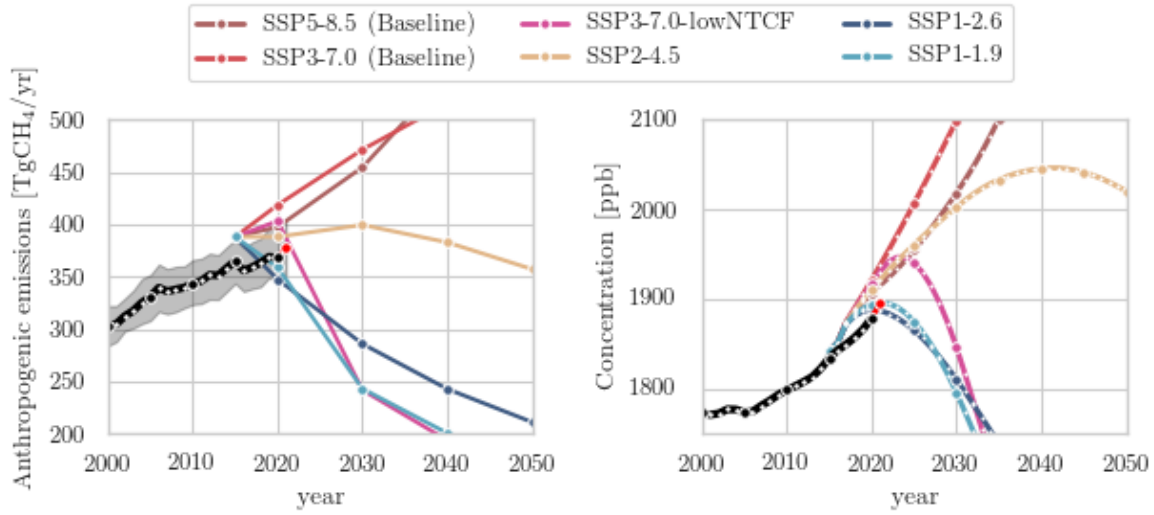
We are really grateful to the reviewer for this encouraging comment and the positive attitude in front of such a long paper

Minor comments
Contents – I think a paper this long warrants a Contents section.

We added this comment in an earlier version. However, unfortunately, a Contents section is not allowed in ESSD. We included the Contents section of the manuscript in the first Section of the Supplementary Material. We advertise this feature at the end of the introduction adding the following sentence: " **For easier reading, the list of Contents of this manuscript is presented in the first section of the Supplementary Material**."

Fig2 and L495-7 – The figure shows 2005 onwards not 2000. Should the figure have been altered at some point?

This is true that Figure 7 starts in 2005. We have modified the figure and it starts now in 2000, consistent with the start of the budget as follows:



L506 - "appear likely to follow the higher-emission trajectories over the next decade in terms of trend, and the peak year has not yet been reached." - this seems a bit too much of an assumption to me. since it is adding depth to a comment on the abstract, I think worth being precise. In fig2 (right) SSP1 and SSP3-7-low pathways show a change from peak growth to rapid reduction of methane over approx 10 years. So it doesn't matter what the trend is now, if it was maximum growth rate we could still have peaked, returned to approx current levels, and be declining in 10 years from now. That is quite different from "likely to follow the higher-emission trajectories". Now, perhaps you think that the preceding progress is not in place to follow those paths or the SSP scenarios are unrealistic, but I'd encourage you to explicitly say that if it's the case.

There was probably a typo, as we meant "past" and not "next". The text has been modified as follows: "**but current emissions appear likely to follow the higher-emission trajectories over the <u>past</u> decade in terms of trend, and the peak year has not yet been reached. <u>High or medium emission reduction rates as suggested by scenarios SSP1 and SSP2 have not yet happened.</u>** "

L1028 - "thus we estimate that ⅓" - is this purely your expert guess? If so, say so. Can you provide any other reasoning for this fraction? Could it actually be anything from 0 to 100%, or is there any reasoning that can be applied to think it's not likely to be entirely arbitrary?

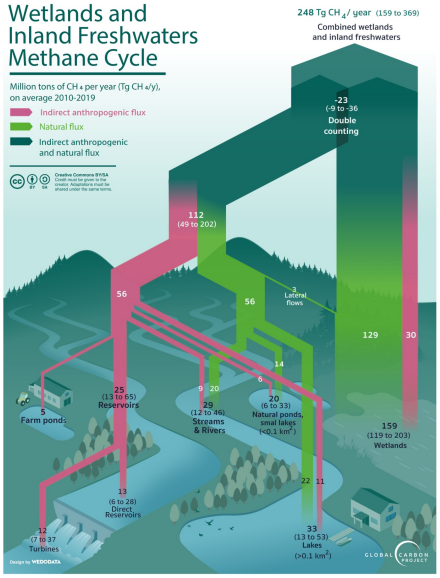
This value of ⅓ has been justified above line 1018, by citing four recent studies on the eutrophication of lakes. <u>⅓ is the lower bond value of the different estimates</u> :" Several recent studies have estimated that anywhere between 30 and 50% of lakes are eutrophic (Cael et al., 2022; Qin et al., 2020; Sayers et al., 2015; Wu et al., 2022). These studies estimate numerical percentages (one by depth class: Qin et al., 2020), but none have estimated the percent of lake surface area that is eutrophic nor have any determined the extent of anthropogenic vs. natural eutrophication. Still, numerous studies have noted widespread increases in eutrophication indicators across lakes due to nutrient loading and warming (Griffiths et al., 2022; Ho et al., 2019; Taranu et al., 2015), thus we estimate that ⅓, or 11 Tg CH4 yr-1 of CH4 emissions from lakes >0.1 km2 could be anthropogenic."
As a result, we believe that the ⅓ has been justified in the text. Further studies would certainly help in reducing this uncertainty.

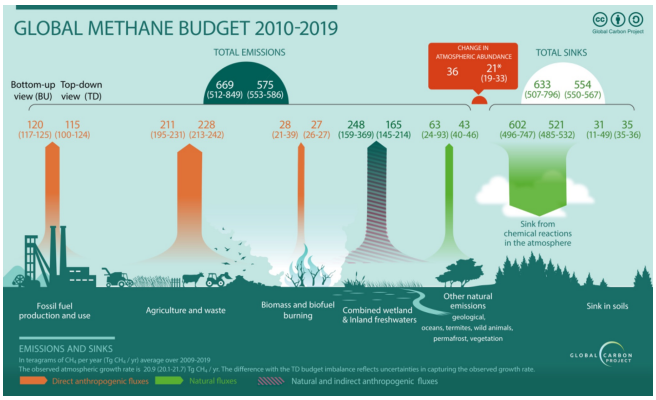
Sec4.1.1 and Fig1b – Some of the clearest peaks in the growth rate are located around significant ENSO events 1997/98, 2015/16, 2020-22. Is it worth a short explanation? Example literature: https://acp.copernicus.org/articles/19/8669/2019/ And as that paper mentions, lightning can influence this variability as well as wildfire (see Murray ref within for such analysis).

Indeed ENSO events have an impact in terms of emissions (biomass burning, or wetlands) and also sinks through OH, however this may not be systematic and depends on the intensity of the ENSO event. However the reviewer is right that we do not comment on the inter annual variability and the link to climate variability. We have added the following sentence and references: ”B**oth climate variability and anthropogenic emission changes are responsible for variations in atmospheric CH_4 growth rates. Indeed, climate variation such as El Nino Southern Oscillation induces changes in emissions such as biomass burning or wetland emission but also impact OH oxidation (e.g., Rowlinson et al., 2019 ; Zhao et al., 2020 ; Peng et al., 2022).**”

Fig 7 – A third colour (e.g. yellow) could be used for “indirect anthropogenic fluxes” and then used to stripe the “combined wetland and inland freshwater” flux as you’ve done for the biomass and biofueld burning flux. Then a note in the caption equivalent to the other caption sentences.

Indeed while reviewing Jackson et al. 2024 we modified the infographic including hatches, but we kept the orange color. Fig 4 has been redesigned so that indirect anthropogenic emissions are presented in pink, and called “indirect anthropogenic emissions” (see below). Figure 7 has also been modified to keep color consistency between the two. A darker green and pink arrow now depict natural and indirect anthropogenic fluxes - only for wetland and freshwater emissions.





L1830 - “tropical” - you do not have a tropical category. You have a tropics + Southern Hemisphere category. I suggest you reword to be more precise at least in first reference. If you then want a sentence to say that you believe this category is dominated by tropical emissions and that you refer to it as “tropical” thereafter, then so be it.

Indeed, this was a shortcut. This has been rephrased to : “**The latitudinal breakdown of emissions inferred from atmospheric inversions reveals a dominance of emissions in the latitudinal band 90S-**

30N of 364Tg…As emissions in the Tropics (30S-30N) dominate this latitudinal contribution, we may refer to 90S-3N as the "Tropics" in the following."

L1830-1837 – Your regional categories are over different sized areas. I think it would be worth noting the area of each here. Your regional percentages may not be proportional to area necessarily, but they are roughly following it.

This is really pertinent! We have calculated the land surfaces (emissions are mostly on land) in km^2:

90˚S - 30˚N (km^2)	30˚N - 60˚N(km^2)	60˚N - 90˚N (km^2)	Total (km^2)
7.094483e+07	4.635364e+07	1.731775e+07	1.346162e+08
52,7%	34,4%	12,8%	100%

In the text, we stated:" The latitudinal breakdown of emissions inferred from atmospheric inversions reveals a dominance of tropical emissions of 364 [337-390] Tg CH4 yr-1 , representing 64% of the global total (Table 5 and 6). 32% of the emissions are from the mid latitudes (187 [160-204] Tg CH4 yr-1) and 4% from high latitudes (above 60°N)." We have added the following sentence:
"**While the amounts of emissions depend on the surface area of the regions, the relative contribution of the emissions is much larger (12 points of percent) than the relative importance of the surface areas for the 90°S-30°N region, on the contrary the boreal regions (60°N-90°N) emissions contribute significantly less than the relative importance of their surface areas (9 points of percent).**"

L2042 – Hopefully the research under the new NERC highlight topic on tropical oxidation will provide some good analysis to feed into the next GMB https://www.ukri.org/opportunity/addressing-environmental-challenges-nerc-highlight-topics-2024/

Indeed, the Tropics play a major role regarding atmosphere oxidation capacity. More data and modeling effort on that topic will be of great help for the global methane budget as OH remains one of the main issues and source of uncertainties for top-down studies.

Technical comments

L205 – typo "s estimated" and a bit confusing how "estimated" also used later in sentence.
The typo has been corrected and the sentence cut in two and rephrased. "**The uncertainty in the chemical loss of CH_4 by OH, the predominant sink of atmospheric CH_4, has been estimated using Prather et al. (2012) and Rigby et al. (2017). The former study estimated this uncertainty at ~10% from the uncertainty in the reaction rate between CH_4 and OH, and the latter study was based on methyl-chloroform measurements."**

L265 – typo? "Saunosi"
The typo has been corrected

Fig4 - "XX to XX" for farm ponds – I don't think this has any general meaning. I suggest just removing, or using question marks, but in the least explaining this term in the caption.
Indeed, we noticed this later on. The figure has been corrected.

L1082 – A bit random how "BU" suddenly starts being used now, given that "bottom-up" is used earlier in the paragraph. I see the abbreviation is used elsewhere. At least define it at first use.
We decided not to use the abbreviation in the text. I have searched for and replaced any remaining BU (or TD) abbreviation.

L1353 - "Increased seepage of geogenic CH4 gas seeps along permafrost boundaries and lake beds may also be considered a direct flux" – please check the phrasing on this text, I'm not sure it makes sense. I wonder if "gas" should be "as".

Indeed. This has been rephrased to "**Increased release of CH4 from deep geogenic sources that occurs as seepage along permafrost boundaries and lake beds may also be considered a direct flux**"

L1971 - "inter annual", "inter-annual" or "interannual" are inconsistently used throughout.
Thank you for spotting this, the text being long with multiple contributors, it happens that there are such inconsistencies. This has been corrected and we consistently now use "interannual".

L2189 - "are sustained increase" typo... "is a" or "increases"
This has been corrected

L2211 – Is the following a normal requirement for a dataset connected to an ESSD publication? I'd normally assume that published data can be used freely for research (without requiring further permission), assuming correct acknowledgement/citation. - "The free availability of the data does not constitute permission for publication of the data."
This is true. The sentence has been removed.

Supp text 1 – subscript missed on "xa" and "Pa"
This has been corrected

Supp materials – Should "Plumer" be "Plummer" throughout references?
This has been corrected

fig_maps_wetlands_anthropogenic.nc - strange how "fos" metadata is poor compared to the other flux variables in this netcdf. I had to go to the supplement to find a reference to "fos".

Indeed, we forgot to add Attributes to the variable "fos" in the submitted files. This has been corrected and the variable has been renamed "flux_ch4_fossils_fuels" for clarity. We really thank the reviewer for spotting this error. The modified files will be uploaded.

References

Peng, S., Lin, X., Thompson, R.L. et al. Wetland emission and atmospheric sink changes explain methane growth in 2020. Nature 612, 477–482 (2022). https://doi.org/10.1038/s41586-022-05447-w

Rowlinson, M. J., Rap, A., Arnold, S. R., Pope, R. J., Chipperfield, M. P., McNorton, J., Forster, P., Gordon, H., Pringle, K. J., Feng, W., Kerridge, B. J., Latter, B. L., and Siddans, R.: Impact of El Niño–Southern Oscillation on the interannual variability of methane and tropospheric ozone, Atmos. Chem. Phys., 19, 8669–8686, https://doi.org/10.5194/acp-19-8669-2019, 2019.

Zhao, Y., Saunois, M., Bousquet, P., Lin, X., Berchet, A., Hegglin, M. I., Canadell, J. G., Jackson, R. B., Deushi, M., Jöckel, P., Kinnison, D., Kirner, O., Strode, S., Tilmes, S., Dlugokencky, E. J., and Zheng, B.: On the role of trend

and variability in the hydroxyl radical (OH) in the global methane budget, Atmos. Chem. Phys., 20, 13011–13022, https://doi.org/10.5194/acp-20-13011-2020, 2020.