Response to Reviewer #1

We thank Reviewer #1 for their comments and their evaluation of our paper. Below, we address each comment in blue.

Reviewer #1

Allen et al. assess the impact of methane (CH4) shortwave absorption for the increase of CH4 concentration from pre-industrial to present-day conditions.

The study builds on previous work (Allen et al., 2023) which has quantified the impact of CH4 shortwave absorption for idealized CH4 perturbations (2x, 5x, 10x pre-industrial CH4). The present study extends the analysis by explicitly simulating the impact for the present-day CH4 concentration, which corresponds to an increase of 2.5x pre-industrial CH4. Consistent with the 2x, 5x, 10x CH4 experiments, the present study finds that shortwave absorption of methane significantly mutes the effect of its longwave absorption. The study extends the analysis by an assessment of the energy budget and by comparing the effect of methane shortwave absorption to the effect of CO2 shortwave absorption.

The results are presented in a clear and understandable way. In my opinion it is a useful contribution to the understanding of the role of methane shortwave absorption. And - considering methane's short atmospheric lifetime – the findings are further relevant for the scientific assessment of short-term climate change mitigation options.

Therefore, I recommend publication after some minor revisions detailed below.

We thank Review #1 for their comments and their evaluation of our paper.

General comment

In my opinion, the paper is clearly written throughout most of the text. However, there are some formulations that might be misleading, especially if used out of context. At some points, the formulations "negative ERF" or "surface cooling" "under SW absorption" are used. I understand that "SW absorption mutes/offsets the (total) ERF" or "the SW effect/contribution to the ERF is negative" is meant. However, especially the formulation "under SW absorption" might be misleading as it could also mean "total ERF/temperature response if SW absorption is accounted for". Therefore, I suggest to carefully review the formulations and adapt the text where it might be misleading.

Some examples are:

- l. 114: "For example, the global mean near-surface air temperature (TAS) response under 5xCH4SW and 10xCH4SW (Figure 1a) yielded significant global cooling at -0.23 and -0.39 K."

We have added additional text to avoid misinterpretation. Here, for example, we have added:

For example, the global mean near-surface air temperature (TAS) response under $5xCH_{4SW}$ and $10xCH_{4SW}$ (Figure 1a) yielded significant global cooling at -0.23 and -0.39 K. We reiterate that this cooling is due to isolation of methane shortwave absorption alone; the total (including methane's longwave absorption) temperature response is significant warming at 0.45 and 0.85 K, respectively (i.e., longwave absorption effects dominate).

- l. 273: "This negative rapid radiative adjustment promotes a negative ERF under methane SW absorption. …"

We have added text to avoid misinterpretation: This negative rapid adjustment promotes a negative ERF under methane SW absorption (we reiterate that the negative ERF is due to isolation of methane shortwave absorption alone; methane's longwave effects still dominate the ERF).

- l. 297: ".., 2.5xCH4SW yields larger (10-20%) and more negative TOA and surface IRFs, ERFs, and ADJs. The larger negative ERFs (and ADJs) act to promote cooling."

I think that the SW contribution to TOA IRF (2.5CH4SW) is not even negative, but weakly positive (Fig. 2a)).

Yes, thank you for catching this mistake, as the TOA IRF here is positive (the surface IRF is negative). We have fixed this: To summarize, relative to $2xCH_{4SW}$, $2.5xCH_{4SW}$ yields a larger positive TOA SW IRF and a larger negative surface SW IRF, as well as larger (10-20%) negative TOA and surface ERFs and ADJs. The larger negative ERFs (and ADJs) act to promote cooling. We reiterate that these values are due to isolation of methane shortwave absorption alone.

- l. 644: The total rapid radiative adjustment for both CO2 perturbations is negative under SW radiative effects at …"

We have added: The total rapid adjustment for both CO_2 perturbations is negative under SW radiative effects at -0.06 W m^{-2} for $2xCO_2$ and -0.40 W m^{-2} for $4xCO_2$ (we reiterate that these negative values are due to isolation of CO_2 shortwave absorption alone; CO_2's longwave effects still dominate the total rapid adjustment and ERF).

- l. 831: "… leading to a negative ERF.

We have added: CO_2 SW absorption yields qualitatively similar results to CH_4 SW absorption, including a negative ADJ that offsets the positive IRF, leading to a negative ERF (Fig. 7; we reiterate that these negative ADJ and ERF values are due to isolation of shortwave effects alone).

Specific comments

l. 80: The term "rapid adjustments" is used in the introduction without a detailed explanation, which follows in the Methods section. Please shortly explain the term in the introduction or refer to the Methods section.

We included a brief description of "rapid adjustments", i.e., surface temperature independent responses. We have added "See Section 2" here, which provides a more complete definition of the term "rapid adjustment".

l. 159: I assume that the simulations are all "time slice simulation" (=cyclic repetition of the boundary conditions every year). This is not explicitly stated.

We included "equilibrium simulations", but we now explicitly also include "time slice simulations (i.e., cyclic repetition of the imposed perturbation)".

l. 209: Here an explicit description how the surface temperature driven feedbacks (e.g. Fig. 5) are calculated is missing. I assume that they are also calculated using the kernel method, but with the climate variable from the coupled ocean experiments. The radiative effects of the slow response are then presumably calculated as difference between radiative effects of the fast and total response?

Yes, this is correct. We included this information in Section 3.4, "We apply the radiative kernel decomposition to the 2.5xCH_{4SW} coupled ocean-atmosphere simulation (Figure 5). The 'fast' responses from the fixed climatological SST runs (i.e., the rapid adjustments) and the surface-temperature-induced 'slow' climate feedbacks (i.e., the difference between the coupled ocean atmosphere and fixed climatological SST simulations) are also included".

We now include this information in the Methods section as recommended by the Reviewer: The total climate response, which includes the IRF, ADJs and the surface temperature response, is quantified using the coupled ocean-atmosphere experiments. Specifically, the radiative effects associated with the total climate response are estimated using the same radiative kernel decomposition as above, but applied to the coupled ocean-atmosphere simulation. The surface temperature responses (i.e., 'slow' response) are estimated as the difference between the coupled ocean atmosphere simulations and the climatologically fixed SST experiments. Similarly, the radiative effects associated with the slow response are calculated as the difference between the kernel-derived radiative effects of the total and fast responses.

Section 3.4 /Fig. 5:

- The second paragraph (l. 443-455) might be moved to section 3.1 as only the rapid adjustments are discussed.

We've decided to keep this paragraph here.

• The radiative effects of the total and slow response are not shown for CH4LW and CH4LW+SW. A figure similar to Fig. 2 b) could be added in the supplement as comparison

The focus here is on the CH_{4SW} radiative effects. Nonetheless, we have added this figure to the Supplement.

Section 3.5.:

I am a bit confused about the sign convention in this section, which makes it difficult to follow the discussion. Could you give more detail on how to calculate LWC and SWC? Do they represent the divergence of LW/SW radiative fluxes in the total atmospheric column (=loss or gain of radiative energy of the total atmospheric column)?

If yes, I would presume that SWC would lead to energy gain (=warming) for reference conditions as the net downward SW flux at TOA is larger than the net downward SW flux at the surface (see e.g. Fig. 7.2 in IPCC-AR6, The Physical Science Basis). The LWC should lead to energy loss (=cooling) for reference conditions as the net downward LW flux at TOA is more strongly negative than the net downward LW flux at the surface, is this correct? The combined effect of LWC and SWC would be cooling (=net energy loss) as the absolute value of LWC is larger than SWC.

Does a positive LWC / SWC represent cooling (= net energy loss) or warming (=net energy gain)?

We have clarified this in the revision: LWC is the net longwave radiative cooling of the atmosphere. SWC is the net shortwave radiative cooling of the atmosphere. The "C" stands for cooling, i.e., positive SWC and LWC represent cooling of the atmospheric column. In CESM2, positive longwave radiative fluxes are upwards, so LWC is calculated as the net LW radiation at the TOA minus that at the surface. In CESM2, positive shortwave radiative fluxes are downwards, so SWC is calculated as the net SW radiation at the surface minus the net SW radiation at the TOA (or equivalently, the negative of the net SW radiation at TOA minus that at the surface). Both terms are positive for cooling (energy loss). SH is the downwards sensible heat flux at the surface (i.e., positive values indicate atmospheric cooling). H is estimated as the residual between L_cP and Q. In the global mean, the circulation term (i.e., H) is zero, implying $L_cP = Q$. As Q is composed of LWC and SWC, this balance shows that condensational heating via precipitation is largely balanced by radiative cooling of the atmosphere.

l. 850: It might be worth mentioning here that chemical composition changes of O3 and stratospheric H2O also affect the temperature response and thereby the static stability in the upper troposphere and stratosphere (see e.g. Winterstein et al, 2019, their Fig. 8; https://doi.org/10.5194/acp-19-7151-2019; for the temperature response induced by O3 and H2O changes in the stratosphere). Could this affect the cloud adjustment processes?

Yes, thank you for making this point, which we have now added to the revision: We reiterate that our simulations do not include these methane indirect effects. Such effects not only impact the

ERF, but also the temperature response in the stratosphere and upper troposphere (Winterstein et al., 2019), which in turn may impact the cloud response.

Typos / technical corrections:

l. 74: Etminan et al., 2016 (misspelled) Fixed.

l. 94 : "… isolate the effect of …" Fixed.

l. 129: estimates (plural) Fixed.

l. 149: "targeted methane-only equilibrium climate simulations"- This implies simulations perturbed by methane only, but you also conducted CO2 experiments. Yes, we have included a note that CO2 experiments are also performed.

l. 217: I assume it is 5% of ERF? Yes, this has been added.

l. 325: Double mentioning of word correlation: "Correlations between … are significant." Fixed.

l. 352: Should the unit of static stability be "K/km"? We calculate lower-tropospheric stability as the temperature difference between 600 hPa and 990 hPa, i.e., units of K. This has been clarified in the revision.

l. 471: Avoid line breaking between - and corresponding number (-0.31 Wm-2). Fixed.

Captions of Supplementary Fig. 1, 4 and 5: "Total climate responses are estimated using from coupled ocean-atmosphere CESM2 simulations." – "using data from coupled ocean-atmosphere simulations" Fixed.

Captions of Supplementary Fig. 2 and 3: "Annual mean global mean spatial fast responses": The data do not show the global mean, but the spatial distribution. Fixed.