

Response to Referee #1 of “The ENSO-driven bias in the assessment of long-term cloud feedback to global warming” by Liu et al.

General comments:

This study investigates the influence of ENSO on cloud feedback estimates under global warming, using a regression-based de-ENSO method. Based on reanalysis observations and GCM simulations, the authors find that ENSO variability biases estimates of long-term cloud feedback to global warming both in the historical record and the abrupt-4×CO₂ experiment, with large impacts on regional scales.

Overall, the paper addresses an interesting topic. However, I have several major concerns regarding the methodology and the main findings. Some of them may arise from a lack of clarity in the Method section. I strongly suggest that the authors improve the clarity of the manuscript, particularly by providing a clearer and more detailed explanation of the main framework.

Answer: We sincerely thank the reviewer for the insightful comments on our manuscript. The detailed feedback has greatly improved the clarity of our work. We have carefully considered all points raised and revised the manuscript accordingly.

Before presenting our specific responses, we begin with a brief summary of the main changes that were made in the manuscript: (1) The Materials and Methods section was carefully revised to describe clearer of the methodology; (2) the analysis of significance tests for all relevant results was added to provide statistical justification; (3) SST from GCMs is now used to compute ONI to ensure consistency; and (4) the text, figures and metric have been improved to better articulate the implications of our findings and to provide stronger justification for the proposed methodology.

Our point-by-point response is provided below, with citations from the revised manuscript and newly added supplementary materials (SI) appearing in *italics*.

Major comments on the methodology:

1. My main question regarding the method: Is the ONI (ENSO timeseries) detrended? This is critical because the proposed linear framework (Eq. 1)

$$Y = a \times \text{time} + b \times \text{ONI} + c,$$

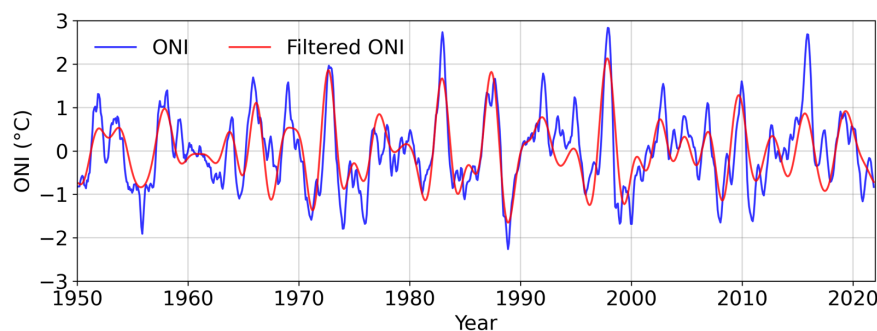
aims to separate the long-term trends (the first term, $a \times \text{time}$) from ENSO-related variability (the second term, $b \times \text{ONI}$). If the ONI itself contains a long-term trend, this could lead to double-counting of changes in the targeted variable (CRE or GMST) that are associated with tropical mean-state SST changes. I'm wondering if this may be the case in the abrupt-4×CO₂ analysis (see more on this below). In its current form, the manuscript doesn't clearly state whether the ONI has been detrended. The text

mentions that the ONI was bandpass-filtered, but the filtering timescale was not specified (it only says “to remove ONI variations beyond ENSO’s typical periodicities”). Also, Line 106 “it retains the ENSO-induced long-term trend effect” seems to suggest the ONI trend is retained. Moreover, Lines 134-136, which discuss results from GCMs, also suggest that no detrending is applied to the ONI timeseries before the decomposition. In either case, more clarification is needed. If the ONI is indeed not detrended, I’m concerned about the linearity of this method and would appreciate the authors’ comments.

Answer: We appreciate this thoughtful comment that is central to our analysis and helped us clarify our method.

Yes, the ONI is detrended when estimating ENSO-related bias (rephrased as “ENSO contribution” in the revised manuscript and hereafter, as it more accurately reflects that we are quantifying the component of the estimated feedback that is linearly attributable to ENSO variability) in cloud feedback estimates (Sections 3.3–3.4). The original ONI (blue curves in Fig. 1) is used only for the general discussion of ENSO impact on GMST (Sections 3.1) and CREs (Sections 3.2).

More specifically, to investigate ENSO contribution, we use the bandpass-filtered ONI (red curve in Fig. 1), which retains only variability within the 2–7 year band. This excludes any (even if naturally occurring) long-term trends (> 7 years) in ONI, ensuring they are not mis-attributed to ENSO.



“Figure 1: Time series of the original ONI (blue curve) and the bandpass-filtered ONI (red curve), derived from ERA5 data during January 1950 – December 2021.”

To better clarify these points, we have revised the corresponding text, as cited below:

Revised text in Section 2.3: “In this study, we use a regression-based ENSO-correction method due to its conceptual simplicity and computational efficiency. Specifically, we first use a bandpass filter to remove ONI variances outside the typical ENSO periodicity band of 2 – 7 years (Fig. 1). This filtering isolates the core ENSO signal and helps to decouple it from other climate perturbations, like long-term trends, the Atlantic Multi-decadal Variability, and the Pacific Decadal Oscillation.”.

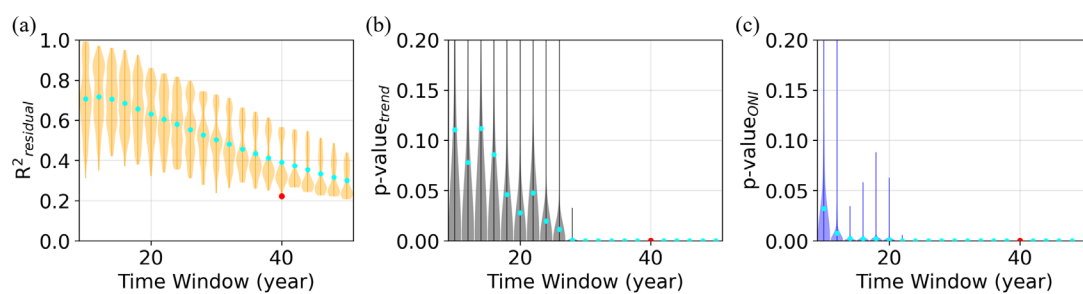
“Importantly, because Eq. (1) uses the bandpass-filtered ONI and assumes no time lag, this OLS-based ENSO-correction method may retain some ENSO-related variations in Y . These include potential low-frequency natural trends in ENSO itself and any delayed

or non-linear impacts of ENSO on GMST and CREs. Consequently, this method is likely to provide a conservative estimate of ENSO contribution (see Section 2.4) (Kelly and Jones, 1996; Compo and Sardeshmukh, 2010).”.

Revised text in Section 3.1: “To quantify this, we calculate the coefficient of partial determination (partial R^2) using OLS multivariate regression models (similar to Eq. (1), but using the original ONI rather than the bandpass-filtered one) and present the results as a function of the time window”.

2. My second methodological concern is related to the residual term (c in Eq. 1): How large is its contribution? Is it sufficiently small that one can justify focusing only on the first two terms, as done in the paper? Figs. 2bc show that the sum of GMST variance explained by the first two terms is notably less than 1, and can be even smaller than 0.5 (depending on the period). This again raises questions about whether this linear decomposition is appropriate and whether the unexplained residual term undermines the interpretation of the results.

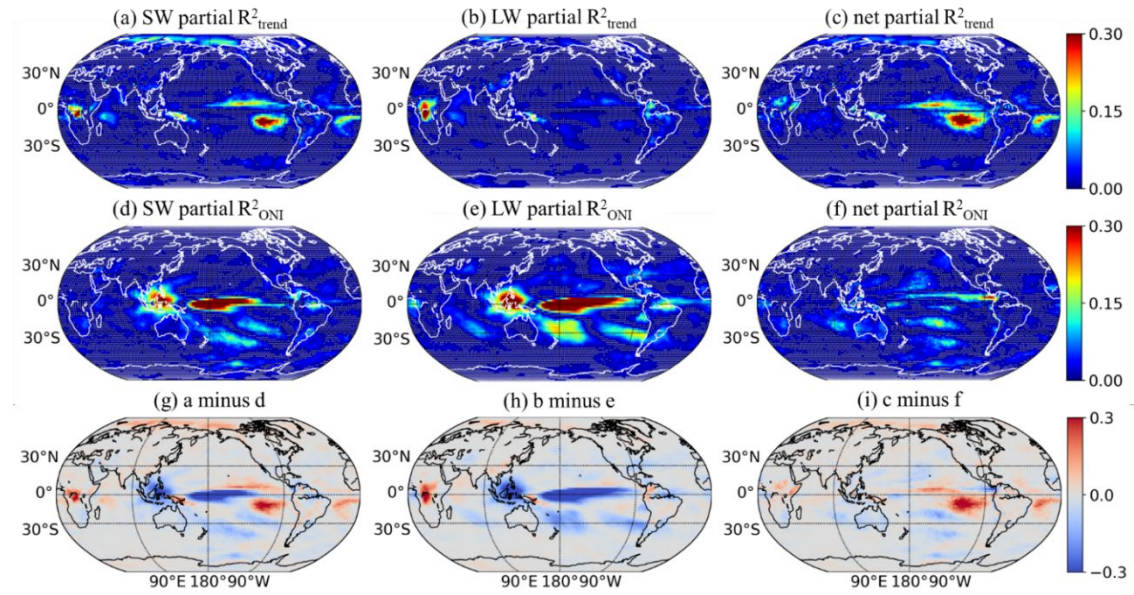
Answer: We thank the reviewer for raising this point. We agree that the two-predictor linear model (time and ONI) explains a limited portion of the total GMST/CREs variance, especially over short time windows (e.g., Fig. S1a). However, we clarify in the manuscript that the primary objective of this regression framework is not to accurately predict GMST/CREs, but rather to isolate the component of variability that is linearly attributable to ENSO (the ONI term). For this purpose of separation, the key criterion is the statistical robustness of the regression coefficients. To this end, we confirmed that the ONI regression coefficient (b in Eq. 1) is statistically significant ($p < 0.05$) across nearly all analyses (e.g., Fig. S1c), even when the explained variance is moderate. This provides confidence that the decomposed ENSO signal is robust and not merely an artifact of residual noise. In the revised manuscript, we have also added significance tests for all relevant analyses to provide statistical justification. The corresponding revised figures (Fig. S1, Figs. 3–5, 7–8) and text appear below:



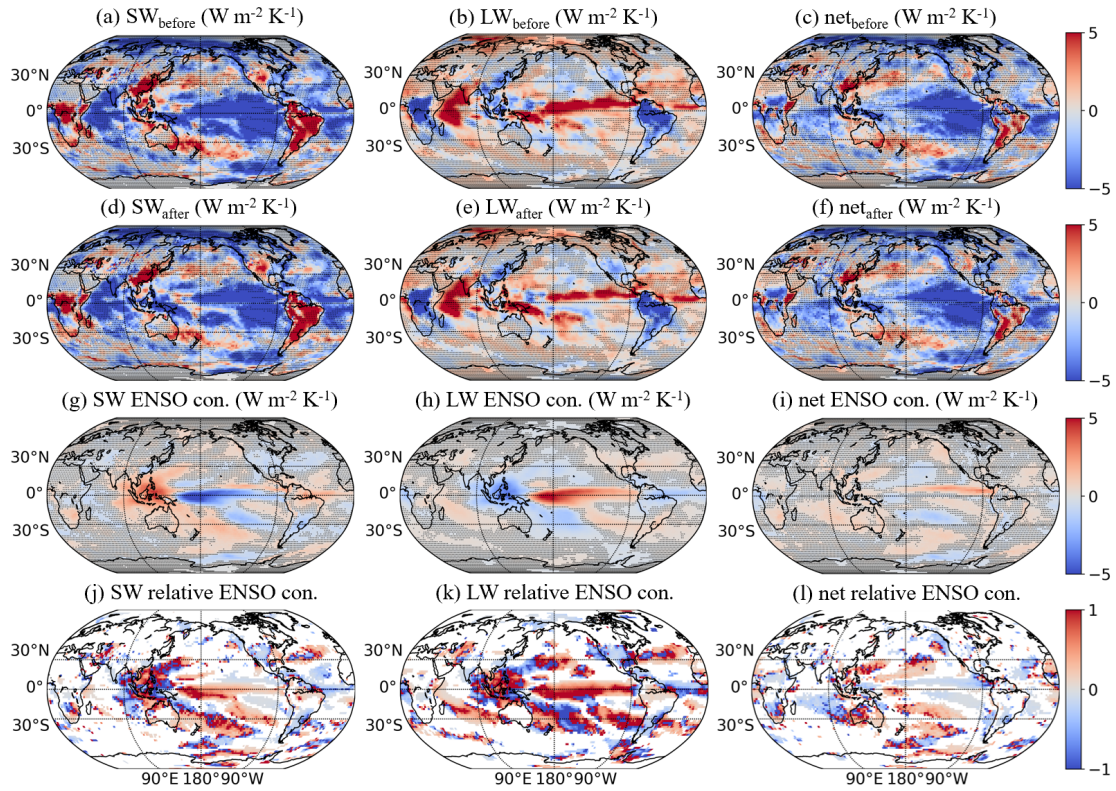
“Figure S1: Violin plots for residual R^2 and P-value of results shown in Fig. 2b – c in the main text. (a) Residual R^2 , (b) p-value of the partial regression coefficient of time (i.e., a in Eq. 1), and (c) p-value of the partial regression coefficient of ONI (i.e., b in Eq. 1).”

Revised text in Section 3.1: “The corresponding test statistics (Fig. S1) suggest that the ONI regression coefficient (b in Eq. 1) is statistically significant at the 95% confidence level across nearly all analyses, even when the explained variance is

moderate. This allows us to assess the relative contribution of the warming trend (partial R^2_{trend} ; Fig. 2b) and ENSO (partial R^2_{ONI} ; Fig. 2c) to the total variance of GMST across different timescales with high confidence.”.

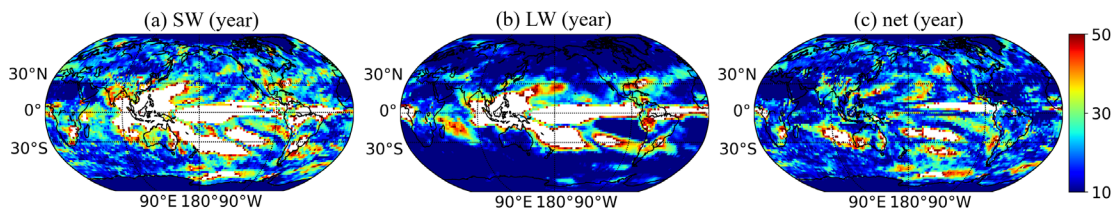


“Figure 3: A sample analysis of the variations in CREs as driven by the temporal trend and ENSO, derived from ERA5 data during January 1982 – December 2021. (a – c) Partial R^2_{trend} for (a) CRE_{SW} , (b) CRE_{LW} , and (c) CRE_{net} . (d – f) Partial R^2_{ONI} for (d) CRE_{SW} , (e) CRE_{LW} , and (f) CRE_{net} . (g – i) The difference between (a – c) and (d – f). In panels (a – f), white dots denote grids with statistically insignificant partial regression coefficients of time (i.e., a in Eq. 1) and ONI (i.e., b in Eq. 1) at the 95% confidence level.”

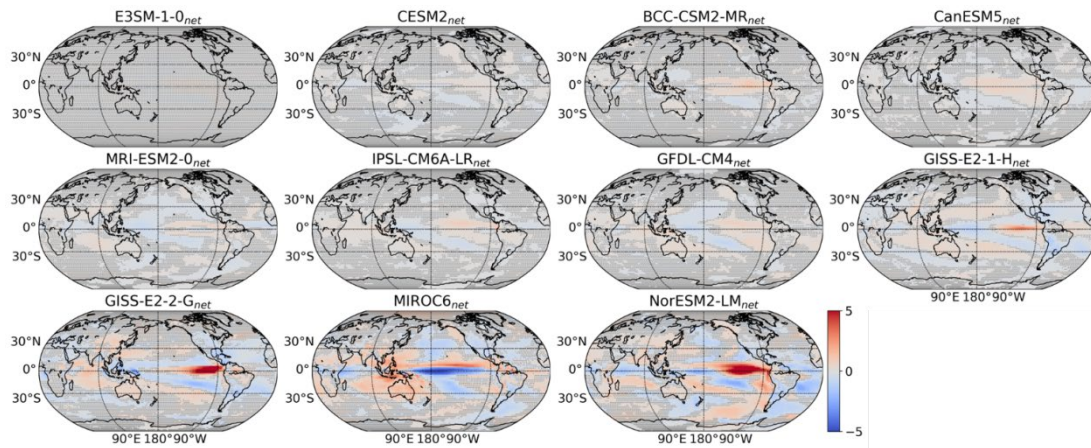


“Figure 4: A sample analysis of ENSO contribution to cloud feedback estimates for CRE_{SW} (left column), CRE_{LW} (middle column), and CRE_{net} (right column), derived from ERA5 data during January 1982 – December 2021. (a – c) Cloud feedback estimates before ENSO correction. (d – f) Cloud feedback estimates after ENSO correction. (g – i) ENSO contribution (a – c minus d – f). (j – l) Relative ENSO contribution (g – i divided by a – c). In panels (a – i), black dots denote grids with statistically insignificant partial regression coefficient of ONI (i.e., b in Eq. 1) for either GMST or respective CRE at the 95% confidence level. In panels (j – l), these insignificant grids are masked in white.”

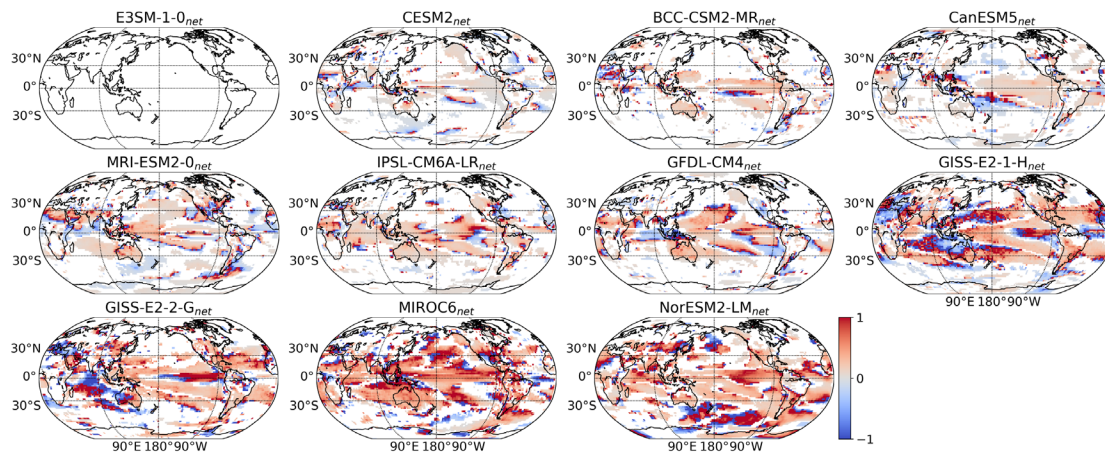
Revised text in Section 3.3: “To quantify this timescale dependence, we calculate the ENSO contribution (e.g., Fig. 4g – i) for the same range of possible periods by applying each time window across the entire 72 years and use a metric we call “ENSO effect minimal time”. This metric is defined as the shortest time window beyond which the mean magnitude of ENSO contribution (ignoring the sign) falls and remains below $1 \text{ W m}^{-2} \text{ K}^{-1}$ (i.e., $|\overline{\text{ENSO con.}}| < 1 \text{ W m}^{-2} \text{ K}^{-1}$), or beyond which the partial regression coefficient of ONI (i.e., b in Eq. 1) for either GMST or CRE becomes and remains statistically insignificant at the 95% confidence level.”.



“Figure 5: Maps of “ENSO effect minimal time” for different CREs, derived from ERA5 data during January 1982 – December 2021. (a) CRE_{SW}, (b) CRE_{LW}, and (c) CRE_{net}. Regions masked in white denote grids where ENSO contribution never consistently falls below $1 \text{ W m}^{-2} \text{ K}^{-1}$ or becomes statistically insignificant within time windows up to 50 years.”



“Figure 7: Maps of ENSO contribution to CRE_{net}, derived from GCM simulations from the abrupt-4 $\times \text{CO}_2$ experiment during the first 150 years. The name of the corresponding model is indicated in each panel. Black dots denote grids with statistically insignificant partial regression coefficient of ONI (i.e., b in Eq. 1) for either GMST or CRE at the 95% confidence level.”



“Figure 8: Maps of the relative ENSO contribution to CRE_{net}, derived from GCM simulations from the abrupt-4 $\times \text{CO}_2$ experiment during the first 150 years. The name of the corresponding model is indicated in each panel. Grids with statistically insignificant partial regression coefficient of ONI (i.e., b in Eq. 1) for either GMST or CRE at the 95% confidence level are masked in white.”

3. Finally, Figure 1 shows that ENSO’s influence on long-term changes decreases with time. Given this, it is unclear to me why the authors choose to focus on an arbitrary 40-yr period (1982–2021) throughout the paper, especially since the ERA5 reanalysis data used in this paper spans from 1950–2021.

Overall, I think the paper suffers from a lack of clarity in the Method section and would benefit from substantial revision and clarification.

Answer: Thank you for this comment. Our primary analyses and conclusions are based on the full ERA5 record (1950–2021). The 40-year period (January 1982 to December 2021) was selected as a representative example to illustrate the method and resulting spatial patterns (e.g., Figs. 3–4) for the following reasons:

(1) Methodological Illustration: as the time-dependence of ENSO contribution is complex, we required a fixed, contiguous period to demonstrate the step-by-step output of our framework in the figures.

(2) Climatological Relevance: As shown in Fig. 2c, the influence of ENSO on GMST stabilizes (i.e., decays very slowly) for periods beyond ~40 years, making this time window a climatologically meaningful timeframe.

(3) Scientific Interest: This period is characterized by a strong warming trend coupled with a relatively weak ENSO signature (red dots in Figs. 2b–c), making it a valuable case for detailed examination due to the expectedly small ENSO contribution to cloud feedback estimates.

In response to this concern, we have clarified this rationale in the revised manuscript, as cited below:

Revised text in Section 2.1: *“To facilitate a walk-through of the methods and results (a sample analysis), a representative 40-year subset (January 1982 – December 2021) is used.”.*

Revised text in Section 3.1: *“The partial R^2_{trend} values increase consistently with longer time windows, suggesting that the warming trend accounts for a steadily growing proportion of GMST variance over extended periods. In contrast, the partial R^2_{ONI} values decrease yet gradually stabilize for periods exceeding ~40 years, indicating a diminishing, though progressively attenuated, influence of ENSO as the timescale lengthens. This inverse relationship implies that ENSO contribution to cloud feedback estimates becomes less substantial in longer analyses. For instance, in the 40-year subset from January 1982 to December 2021 (red dots in Fig. 2b – c), the warming trend explains approximately 74% of GMST variance, whereas ENSO accounts for only about 4%. The co-occurrence of this strong warming trend and the relatively weak ENSO signature, along with the stabilization of R^2_{ONI} beyond 40 years, makes this period particularly informative for examining ENSO contribution to cloud feedback estimates. It is therefore selected as a representative example to illustrate the methodology and resulting spatial patterns in Figs. 3 – 4”.*

Major comments on the Results:

1. CRE decomposition in Fig. 3

According to Eq. 1, the linear framework decomposes total CRE variations into two components: (1) a linear trend term ($a \times \text{time}$) and (2) the portion associated with ENSO variability ($b \times \text{ONI}$). In Fig. 3, however, term (1) is interpreted as the CRE change driven by the warming trend, which I find difficult to justify. It assumes that the trend in CRE is equivalent to the CRE response to long-term warming, which may not be valid. This issue may arise from ambiguity in Eq. 1. Specifically, what is the unit of the coefficient a ? Is it the trend unit of the targeted variable (e.g. for CRE, it would be $\text{W/m}^2/\text{year}$), or is it a regression coefficient with respect to long-term global warming ($\text{W/m}^2/\text{K}$)? If it's the former (seems more likely based on Eq. 1), I do not think it can be interpreted as "CER due to warming trend". Either way, this concern highlights a fundamental confusion in the framework that needs to be clarified.

Answer: Thanks for raising this point. The unit of regression coefficient a in Eq. (1) is $\text{W m}^{-2} \text{ year}^{-1}$ for CRE. To avoid potential confusion, we have replaced "warming trend" with "temporal trend" throughout the revised manuscript.

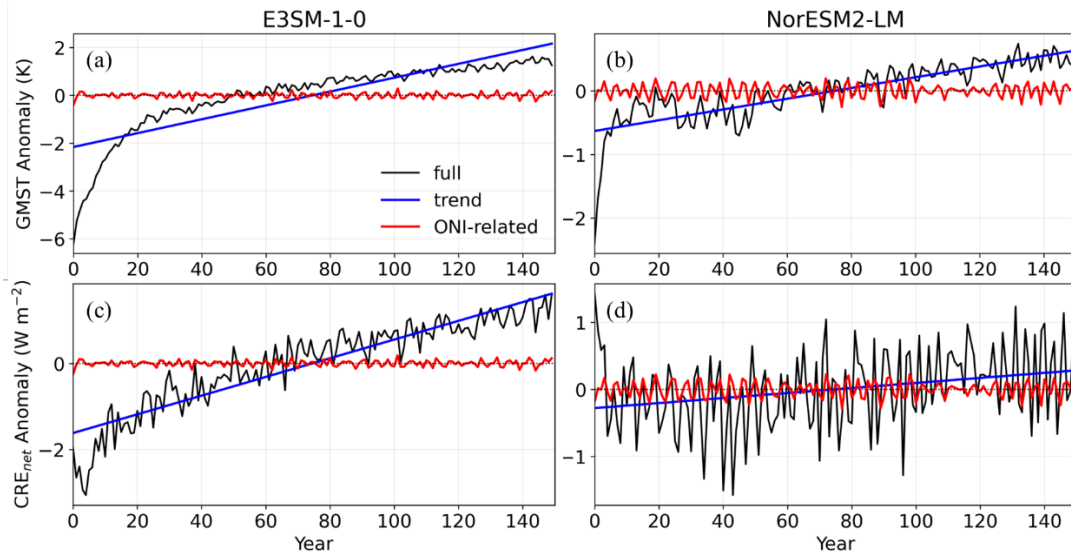
2. ENSO-related biases in $4\times\text{CO}_2$ experiment

I was quite surprised by the (really) large ENSO-related biases in cloud feedback estimates from the 150-yr abrupt $4\times\text{CO}_2$ simulations (Figs. 6, 7), considering (1) the long timescales (150-yr) of the experiment and (2) the potential high signal-to-noise ratio in this strong forcing scenario. It again raises concerns related to the methodological question of whether the ONI has been detrended. If the ONI timeseries contains a strong linear trend in this case, the trend could actually reflect forced mean-state changes rather than ENSO variability. In that case, the current method might be attributing part of the long-term signal to ENSO, thus overestimating the ENSO-related contributions by double-counting tropical Pacific SST trends.

To address this, I suggest the authors show the timeseries of GMST and global-mean CRE over the course of the simulations, either for each model or one representative model. It should include both the full variations as well as their decomposed components (the long-term trends and ENSO-related variations). This would allow us to directly assess the evolution and relative magnitude of the two terms, and to verify whether the ENSO related signals are not being mixed with the global warming trend.

Answer: We appreciate this detailed feedback that actually underscores a key finding of our study. As noted in our response to major comment #1 (on methodology), the ONI is detrended when estimating ENSO contribution to cloud feedback estimates.

Following the suggestion, we have included the analysis of two representative GCMs and shown the corresponding results in Fig. S6. The two selected GCMs are E3SM-1-0, which shows almost negligible ENSO contributions, and NorESM2-LM, which shows strong ENSO contributions (Figs. 7–9). For both models, the time series of GMST and global-mean CRE_{net} show clear separation between the trend- and ONI-related variations using our regression-based deENSO method (rephrased as "ENSO-correction method" in the revised manuscript).



“Figure S6: Decomposition of GMST and global-mean CRE_{net} , derived from 2 GCM simulations from the abrupt- $4\times CO_2$ experiment during the first 150 years. (a–b) GMST of (a) E3SM-1-0 and (b) NorESM2-LM. (c–d) Global-mean CRE_{net} of (c) E3SM-1-0 and (d) NorESM2-LM. The blue and red lines present the trend- and ONI-related variations, respectively.”

Revised text in Section 3.3: “The timeseries of GMST and global-mean CRE_{net} for two representative GCMs (E3SM-1-0 and NorESM2-LM) are also shown in Fig. S6. The results suggest a clear separation between the trend- and ONI-related variations achieved by our regression-based ENSO-correction method, thereby providing further validation for the ENSO contribution obtained by this method.”.

Specific comments:

1. Figure 1: The filtered ONI timeseries appears to have removed much of the high-frequency variability rather than the low-frequency variability?

Answer: We thank the reviewer for this attentive observation. The bandpass-filtered ONI retains only variability within the canonical ENSO band, specifically periods between 2 and 7 years. Consequently, both lower-frequency variability (periods >7 years, e.g., interdecadal trends) and higher-frequency variability (periods <2 years) were removed. The mentioned visual illusion may stem from the fact that the original ONI index exhibits only an insignificant long-term trend during the study period, as discussed in Fig. 2a. The revised text explains it: “*In contrast, the ONI does not exhibit a statistically significant trend (blue dashed line), indicating no consistent long-term intensification or weakening of ENSO over recent decades.*”

2. Line 85: Why not use SST (a readily available variable in GCM output) to compute the ONI to be consistent with observations.

Answer: Thank you. In the revised manuscript, we have followed the recommendation to compute ONI directly from the models' SST to ensure consistency. The results are

almost identical to the previous ones.

3. Line 105-106: what “delayed components of ENSO-related variations” are referred to here?

Answer: The corresponding text has been revised to clarify this point: *“Importantly, because Eq. (1) uses the bandpass-filtered ONI and assumes no time lag, this OLS-based ENSO-correction method may retain some ENSO-related variations in Y. These include potential low-frequency natural trends in ENSO itself and any delayed or non-linear impacts of ENSO on GMST and CREs. Consequently, this method is likely to provide a conservative estimate of ENSO contribution (see Section 2.4) (Kelly and Jones, 1996; Compo and Sardeshmukh, 2010).”*.

4. Line 135: Does this mean that 9 out of 12 GCMs actually show a significant ENSO/ONI trend over this period? If so, does this linear decomposition still hold?

Answer: Yes, that is correct. In the revised manuscript, 9 out of 11 evaluated GCMs show a statistically significant ONI trend over January 1950–December 2014. Simulations from TaiESM1 are excluded from the analysis because we were not able to download the corresponding SST data.

Nevertheless, such ONI trends would not undermine the analysis of ENSO contribution in cloud feedback estimates since it uses the filtered ONI (detrended). Please see our answers to the major comment #1 (on methodology) and #2 (on Results) for details.

5. Line 143-144: This sentence is very confusing and unclear, I do not understand what is meant here. Please consider rephrasing.

Answer: The sentence has been rephrased to *“This allows us to assess the relative contribution of the warming trend (partial R^2_{trend} ; Fig. 2b) and ENSO (partial R^2_{ONI} ; Fig. 2c) to the total variance of GMST across different timescales with high confidence.”*.

6. Line 149: Based on Fig. 2b, the variance in GMST explained by the trend over a randomly-selected 40 yr period (other than 1982-2021) can be as low as 0.3. Similarly, ENSO’s contribution (R^2_{ONI}) is up to 0.1. This suggests that more than 50% of the total GMST variance could come from the residual term. If so, this linear decomposition doesn’t seem to work well and may not accurately reproduce the original variance.

Answer: We appreciate this thoughtful comment and fully acknowledge the limitation of the two-predictor linear model in representing the total GMST variance. Nevertheless, we respectfully emphasize that the main goal of this study is to decouple ENSO impact. To provide statistical justification and ensure the robustness of the decomposed signal, we have added significance tests for all relevant analyses. Please see our answer to the major comment #2 on methodology for more details.

7. Line 165: What exactly is meant by “covariations between clouds and the warming

trend”? As noted in my major concerns, is this essentially just the trend in CRE?

Answer: The text has been revised for clarity to “*Given the significant warming trend in GMST during this period (0.02 K year^{-1}), the resulting patterns reveal strong co-variations between CREs and recent warming in regions such as the Arctic, central Africa, and the tropical eastern oceans.*”.

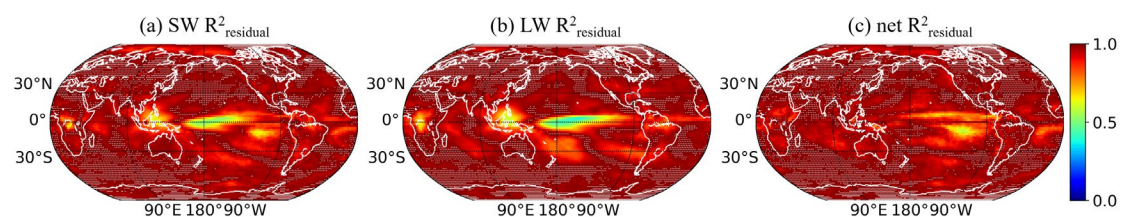
8. Line 169: While it’s true that ENSO has a relatively small impact on the GMST during this period, it may have a more notable impact on regional surface temperature variations (e.g. in the tropical Pacific). If so, this statement may be unfair. For a more solid comparison, I suggest the authors show spatial maps of surface temperature variance explained by the warming trend and by ENSO (similar to Fig. 3 but for TS instead of CRE). In addition, it would also be helpful to show the global-mean CRE timeseries along with its decompositions into the linear trend and ENSO-related component (similar to Fig. 1 but for global-mean CRE instead of GMST).

Answer: Thanks for raising this point. Following this and previous comments, Fig. 3 has been reproduced (please see above), while the statement has been revised into “*Compared to ENSO, the temporal trend has a much weaker impact on CREs over a large portion of low- to mid-latitude oceans (bluish shades in Fig. 3g – i). This is particularly evident for CRE_{SW} and CRE_{LW} across the tropical Pacific, implying a region-dependent ENSO contribution to the assessment of long-term cloud feedback to global warming.*”

9. Related to Fig. 3: how much of the regional variance is associated with the residual term? It would be informative to provide another row of panels showing the contribution of the residual term (c in Eq. 1).

Answer: We thank the reviewer for this suggestion. We have added the analysis and shown the maps of residual variance corresponding to Fig. 3 in Fig. S2. As the reviewer anticipates and we previously discussed, the two-predictor linear model does not capture the total CRE variance, especially for regions with insignificant contributions by both the temporal trend and ENSO.

Nevertheless, since our main goal is to isolate ENSO impact rather than to predict CRE fully, we focus on the statistical significance of the regression coefficients, which has been thoroughly evaluated and added throughout the revised manuscript. Further discussion can be found in our answers to major comment #2 (on methodology) and specific comments #6.



“Figure S2: Maps of residual R^2 for results presented in Fig. 3 in the main text. (a) CRE_{SW} , (b) CRE_{LW} , and (c) CRE_{net} . White dots denote grids with statistically insignificant partial regression coefficients of both time and ONI (i.e., a and b in Eq. 1) at the 95% confidence level.”

Revised text in Section 3.2: *“To illustrate this point, we analyze the same 40-year period (January 1982 – December 2021) as an example and present the corresponding partial R^2 maps of CREs in Fig. 3. The maps of corresponding residual R^2 are shown in Fig. S2.”.*