Reply to reviewers for the manuscript egusphere-2025-1924:"Constraining the time of emergence of anthropogenic signal in the global land carbon sink"

Na Li, Sebastian Sippel , Nora Linscheid , Miguel D. Mahecha , Markus Reichstein , and Ana Bastos

We thank the reviewers for the productive and constructive comments. Here we reply to the comments in detail, and we suggest how to adjust the manuscript according to the comments. In addition, based on the comments, we made some extra changes in the manuscript for easier reading and understanding (at the last of each reply).

Below we address the changes according to the comments **(the line numbers in replies are according to the new manuscript that shows changes**). The blue colored lines are my replies, and the red words are locations changed.

Changes according to the reviewer #2:

Specific comments:

General Comments

The manuscript examines the Time of Emergence (ToE) in both historical and future simulations derived from Earth System Models (ESMs), analyzing their spatial patterns and applying a dynamic adjustment approach to reduce the influence of circulation variability and thereby shorten detection time. The study addresses an important topic with potential implications for early climate change detection. However, the manuscript would benefit from a clearer explanation of the methods section and the addition of a dedicated discussion section. Several figures could also be improved to enhance clarity and interpretability. So I suggest a minor revision before the publication.

We thank the reviewer for the positive and constructive evaluation.

Specific comments

Title:

The use of the word “constraining” in the title may be somewhat misleading, as the manuscript primarily focuses on examining the Time of Emergence (ToE) and detection approaches, rather than directly constraining ToE. Consider revising the title to better reflect the core content and objectives of the study.

We thank the reviewer for pointing that out, we changed the title to: "~~Constraining the time of emergence of the anthropogenic signal in the global land carbon sink~~ Understanding the time of emergence of the anthropogenic signal in the global land carbon sink"

Methods:

Line 140: The meaning of "dynamic" in this context could be clarified. Is it related to dynamically adjusting the time window of the time series? Additionally, the connection between ridge regression and dynamic adjustment is unclear—does ridge regression serve as a method of dynamic adjustment here?

The dynamical means…, ridge regression is one methos of dynamic adjustment. We changed in line 154: “Here, we employ ridge regression, a ~~linear statistical learning~~ dynamic adjustment technique, to estimate…”

Line 235: This paragraph appears to overlap in content with the one beginning at line 219. Consider merging or clarifying to avoid redundancy.

Thanks for pointing this out, we remove the paragraph in line 273:

> "~~In the historical simulations, the land carbon sink (NBP) shows large year-to-year variability, delaying the detection of anthropogenic signals. In contrast, GPP and TER are primarily driven by anthropogenic perturbations, with relatively lower natural variability. The compensating trends of TER and GPP delay NBP detection, explaining why GPP and TER detect the signal in around 10 years, while NBP takes around 26 to 66 years. Next, we explore how the different future climate scenarios impact ToE.~~"

Section 2.4: The calculation of signal (S) and noise (N) would be clearer if accompanied by explicit equations and provided why linear regression is suitable for this purpose. Is S calculated as the slope of the regression of annual mean NBP versus year? And is N the standard deviation across all years (e.g., 1930–1959), or computed year-by-year? The definition of the time window in this section also seems inconsistent with the earlier discussion in Section 2.1.3. Further clarification would be helpful.

We thank the reviewer for highlighting this point, here we clarify the S and N definition in section 2.3.1 Line 130-136:

> "The signal (S) refers to the anthropogenic perturbation driven response, which is ~~given by~~ the linear ~~trend~~ regression slope of the ensemble mean of the simulations for each model (Bonan et al., 2021). For the calculation of N, we first gather a data pool including all ensemble residuals from simulations in the selected period, then mix the data from all years in the selected period together and calculate the standard deviation. In the historical simulations, the noise (N) corresponds to the standard deviation of the ensemble before the ~~1950s~~ 1960s (here is 1930—1959), a period less affected by human activities compared to more recent ones, and used as the baseline for natural variability (Bonan et al., 2021)."

We also added one paragraph explaining why linear regression is suitable for this purpose. In line 140:

> "Here we use a linear regression slope rather than a nonlinear approach to represent the signal trend, the reasons are: 1) Capturing the dominant forced signal. The ensemble mean of NBP, GPP and TER reflects the forced ecosystem response, including anthropogenic forcing, short-period natural forcings (e.g., volcanic eruptions), and decadal internal variability (Deser et al., 2012b; Canadell et al., 2021; Eyring et al., 2021; Mercado et al., 2009; Zhang et al., 2021). The linear trend captures the most consistent anthropogenic influence, whereas nonlinear methods risk overfitting and misattributing natural or internal variability to anthropogenic signals, especially at regional scales where variability is larger (see Figure A.1 and Figure 3). "

Line 178: Are the reported values global means? It would be useful to clarify whether the reduction in detection time applies across all pixels in the study area or only a subset.

Additionally, do the same regions show a reduction after adjustment compared to before?

Thanks, all the reductions reported here are based on global scale, as we consider the test for regional and pixels beyond the scope of this study. In line 184, we added:

> "4) Noise reduction through dynamical adjustment: Given the large year–to–year variability in NBP, we use ridge regression to remove the circulation induced variability in global NBP. To assess the effectiveness of ToE reduction on a global scale through dynamical adjustment…."

Line 182: Please confirm whether V_0 refers to the original ToE value or some other values. If it is the ToE value, the sentence could be rephrased for improved clarity:

"VR is the residual after the circulation-induced variability estimated by the ridge regression model is removed."

→ "VR is the ToE estimated from the residual time series after removing circulation-induced variability using the ridge regression model."

We thank the reviewer for pointing this out. We used this equation to calculate ToE reduction, but also for N reduction (as is shown in Table A.1-A.4). Here we clarify below in line 192:

> "Note that V_O represents the original value (ToE or N) and V_R is the (ToE or N) estimated from the original time series (NBP or GPP) ~~residual~~ after removing the circulation-induced variability estimated by using the ridge regression model ~~is removed~~."

Results:

Section 3.3: It might be more effective to show the future ToE results (currently in supplementary) as the main figure for this section, given that Section 3.3 primarily discusses ToE. Including such a figure could better support the narrative and conclusions.

Thanks. We added Figure A.9 (Heat map of ToE, noise, and signal of NBP under future scenarios.) up as new Figure 5. Note that we changed the noise period from 2020-2050 to 2020-2070, so the values in new Figure 5 are slightly different.

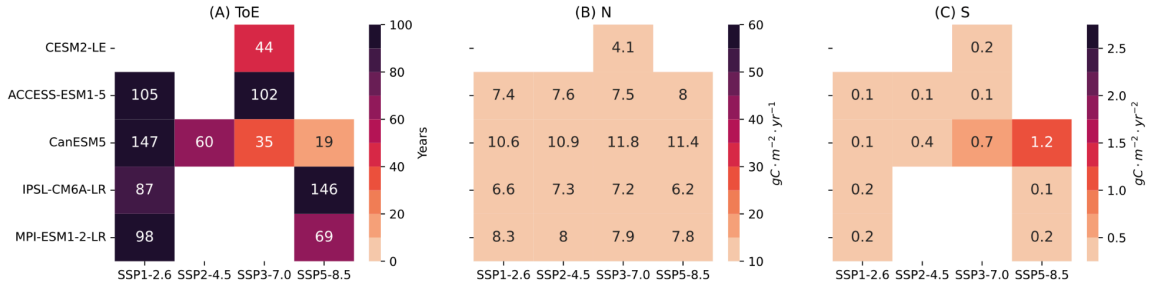

Figure 5. Heat map of ToE, noise, and signal of NBP under future scenarios.

Figure Clarifications

Figure 3: It would be helpful to include a legend or figure caption clarification for the lines shown. Indicating the meaning of the lines, units used for ToE, and spatial resolution would enhance the figure's interpretability.

Thanks for pointing out, we improved Figure 3 as below and also clarified details in the caption.

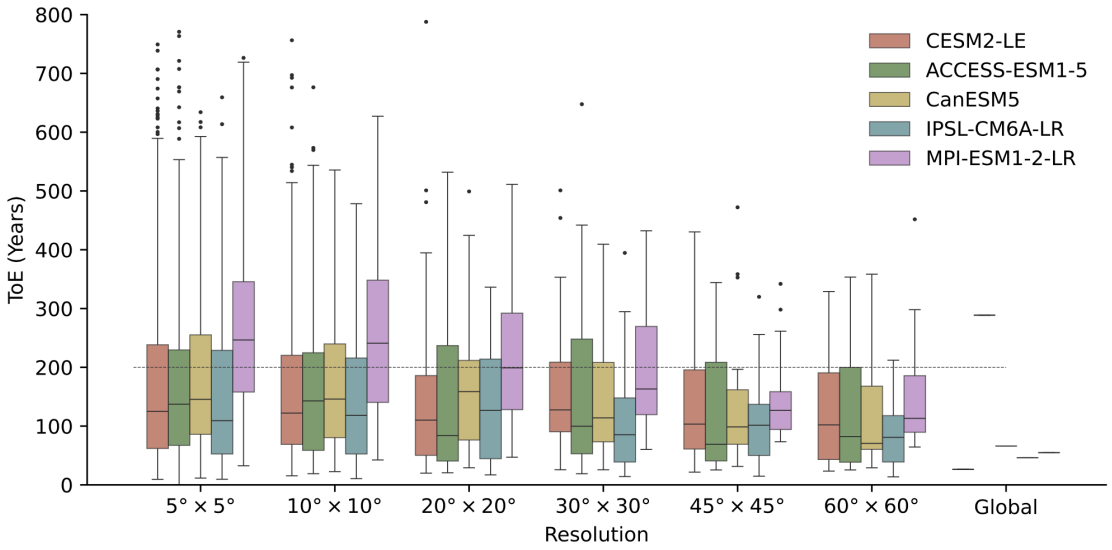

Figure 3. Spatial effect in NBP historical simulations across five ESM large ensembles. The distribution of ToE (years after 1960) ~~are~~ is shown for varying spatial resolutions. The line within each box indicates the median. Note that all ~~the~~ signals are in absolute values, so the calculated ToE are all positive.

Figure 5: The legend and color scheme are somewhat difficult to interpret. Consider using a more intuitive design—e.g., solid boxes for the original time series and hatched or patterned boxes for the residuals.

Thanks for suggesting this, we improved the Figure 5 (new Figure 6). Note that we changed the noise period from 2020-2050 to 2020-2070, and also only included ToEs with value less than 150 years. The similar plot for GPP also changed accordingly.

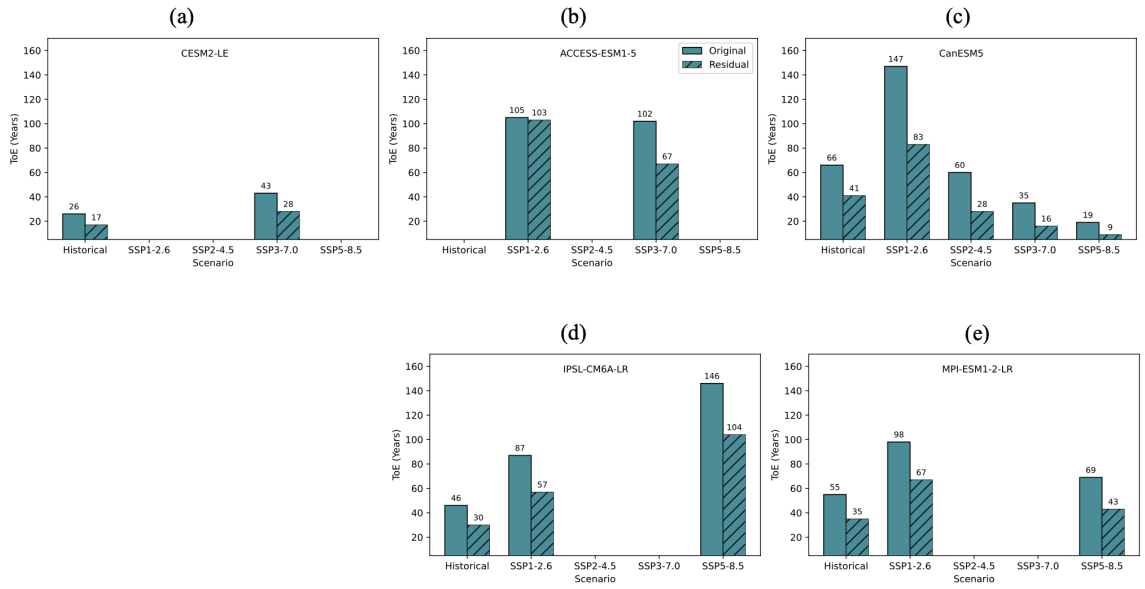

Figure 6. ToE of NBP from historical simulations to future scenarios. Note that ToE in historical simulations is calculated with signal period of 1960–2009 relative to the noise period of 1930–1959, and ToE in future scenarios is calculated with signal period of 2020–2070 relative to the noise period of 2020–2050, details please check Sect. 2.4. The ~~light colored~~ solid boxes represent the ToE of NBP, while the ~~neighboring darker shaded, black framed~~ hatched boxes represent the ToE of the NBP residual with the circulation induced variability removed. In cases where both boxes are missing, the respective ~~simulation was not available.~~ signal is not available (no significance of linear trend slope), or the ToEs are longer than 150 years.

Grammar/typo errors

Line 142: “circulation” → “Circulation”

Thanks, in line 150 we changed to: “Ce~~C~~irculation induced variability”

Lines 152–157: Please revise for grammar.

Thanks, we have corrected in line 159 as:

> “The key steps include (Sippel et al., 2019; Li et al., 2022): 1) Select~~ing~~ pixel-based time series of global SLP to predict global carbon cycle variability~~; here, the full global domain~~. Then calculate the mean seasonal SLP. ~~Since~~ Because DJF (December~~, January, and~~ –February) SLP ~~has~~ provides the highest predictability of annual NBP (~~details please check see Li et al. (2022)~~ see Li et al., 2022 for details), ~~here we select~~ we use DJF SLP in this study. 2) Select~~ing~~ the time series ~~to represent~~ representing global carbon cycle variability ~~as target variable~~; here, this corresponds to the global annual NBP with the ensemble mean removed. 3) Training and testing~~.~~ Split~~ing~~ the dataset into training and testing groups; here, ~~we select~~ the first half ~~period~~ of the dataset ~~as the training group~~ is used for training ~~group~~ and the second half ~~as the~~ for testing ~~group~~.”

Lines 168–169 and 174: These sentences contain grammatical issues and should be revised for clarity.

> Line 176-177: “We perform four statistical analyses: 1) ToE in land carbon fluxes from historical simulations~~:~~. We analyze the ToE ~~time to detect~~ of the anthropogenic perturbed signal in NBP, GPP, and TER in the historical simulations.”
>
> Line 180-182: “2) Spatial effects on ToE~~:~~. We examine how the ToE varies globally and across the 10 RECCAP-2 regions. ~~Additionally~~ In addition, we evaluate the ~~impact~~ influence of spatial resolution on ToE. We calculate ~~by calculating~~ pixel-based ToE values at ~~various~~ multiple spatial scales (ranging from 2.5° × 2.5° to 60° × 60°) and compare ~~comparing~~ these with the global scale.”

Line 102: “10distinct” → “10 distinct”

Thanks, we changed accordingly in line 106.

Additional changes.

1. Line 7-8: Our results show that, firstly, the anthropogenic signal in the global net land carbon sink emerges from 26 to 66 years in the period 1960–2009 ~~2019~~

2. Line 10: “Furthermore, we find that long-term trends of net land carbon sink on most regional scales take at least 20 years more to emerge, due to large~~r~~ contributions from internal climate variability and detected weak signals at smaller scales.”

3. Line 65-66: “The externally perturbed signal (dominated by anthropogenic signal) emerges as the ensemble mean, that is, a deterministic signal.”

4. Line 68-69: “the "time of emergence (ToE)" can be determined as the time required for an external perturbed signal (mostly anthropogenic-caused climate change) to become…”

5. Line 75-78: “Here, we evaluate how long it takes for long-term trends in the global land carbon sink—primarily~~, mostly~~ driven by anthropogenic perturbations—to be detected ~~from local to global scales~~ at different spatial scales. ~~, by estimating the~~ To achieve this, we estimate the ToE in ESM simulations under historical and future scenarios. ”

6. All "circulation induced” to "circulation-induced”

7. Line 155-156: "In our model, the sea level pressure (SLP) field is used as a predictor of NBP variability and as a proxy of ~~circulation-induced variability predict the~~ circulation-induced variability.”

8. Line 156-157: “As a regularized linear regression method, ridge regression allows for including full spatiotemporal dynamics of circulation variations while overcoming multicollinearity and overfitting, which typically arise ~~normally raising~~ from a large number of predictors and relatively short study period.”

9. Line 160: “Select pixel based time series of global SLP, to be used later for predicting ~~predict~~ global carbon cycle variability.”

10. Line 162-163: “ 2) Select the time series representing global land carbon ~~cycle~~ variability; here, this corresponds to the global annual NBP with the ensemble mean removed. ”
11. We remove the definition of SSP, since the detailed discussion can be found in IPCC report in line 109.

    “The future scenario simulations are modeled under different Shared Socioeconomic Pathways (SSPs) for the period 2015-2100, based on varying levels of human-emitted CO2 and mitigation efforts (Chen et al., 2021; Lee et al., 2021; O’Neill et al., 2016)~~:~~.

~~1. SSP1-2.6, CO2 emissions decrease and reach net zero by 2050. Global surface air temperature averaged over 2081-2100~~
~~is 0.5◦-1.5◦ higher than in 1995-2014 (Chen et al., 2021; Lee et al., 2021; O'Neill et al., 2016).~~
~~2. SSP2-4.5, CO2 emissions remain steady until 2050, with global surface air temperature averaged over 2081-2100 is~~
~~1.2◦-2.6◦ higher than in 1995-2014 (Chen et al., 2021; Lee et al., 2021; O'Neill et al., 2016).~~
~~3. SSP3-7.0, without additional climate policies, CO2 emissions doubled by 2100, leading to the global surface air temper-~~
~~ature averaged over 2081-2100 increase of 2.0◦-3.7 ◦ relative to 1995-2014 (Chen et al., 2021; Lee et al., 2021; O'Neill~~
~~et al., 2016).~~
~~4. SSP5-8.5 Without additional climate policies, CO2 emissions doubled by 2050, with global surface air temperature~~
~~averaged over 2081-2100 rising by 2.4◦-4.8◦ relative to 1995-2014 (Chen et al., 2021; Lee et al., 2021; O'Neill et al.,~~
~~2016).~~"

12. Other values are slightly changed due to the changes of noise period from 2020-2050 to 2020-2070, in future scenarios. Also, the ToE values are cut until 150 years.