Supplementary Materials

Hajima et al. “Consistency of global carbon budget between concentration- and emission-driven historical experiments simulated by CMIP6 Earth system models and suggestions for improved simulation of CO2 concentration”

Table S1

The average (AVE), standard deviation (STD), min (MIN), and max (MAX) values of cumulative land and ocean carbon uptake of ensemble members simulated by MIROC-ES2L and UKESM-1-0-LL.



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Figure S1. Global surface air temperature (GSAT) anomalies in (a) C-HIST and (b) E-HIST simulations. Panels (a) and (b) present GSAT anomalies corrected by the GSAT drift found in the control runs (C-PI and E-PI). The drifts were evaluated using linear regression lines and are presented in (c) and (d). Line color represents each model and the representation is the same as that in Figs. 4–7.

アプリケーション が含まれている画像

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Figure S2. Simulated result of C-HIST (left column) and E-HIST (right) by each model. From the top to the bottom, cumulative fossil fuel emission (panel a and h), cumulative land use change emission (b), CO2 concentration (c and i), cumulative land carbon uptake with (d and j) and without (e) land use change impact , cumulative ocean carbon uptake (f and k), and GSAT anomaly (g and l). In panels c and h, prescribed data used to drive C-HIST and E-HIST respectively are shown by black lines. In other panels, the result from each model is shown by colored lines. The vertical gray bars (except for panels g and l) present the estimation range of GCB2021. It should be noted that GCB2021 does not report land carbon uptake with consideration of the impact of land use change (*CL*), and thus it is estimated here as *CL* = *CLN − ELUC* and . All datasets shown here are drift-corrected.

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Figure S3. Same as Fig. 5 but the compatible fossil fuel emissions (x-axis) are not corrected by the imbalance terms.

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Figure S4. Same as Fig. 6 but the compatible fossil fuel emissions (y-axis) are not corrected by the imbalance terms.

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Figure S5. Comparison between initial vegetation carbon in C-HIST and cumulative land use change emission.

### Supplementary section S1: Comparison with GCB2021 in terms of simulated CO2 concentration and compatible fossil fuel emission

In Fig.5b, it was confirmed that good correlation exists between *EFFC-HIST* and *CO2E-HIST*, both of which are indicators for characterizing the carbon cycle response to external forcing in C-HIST and E-HIST, respectively. This suggests that better performance of *EFFC-HIST* likely leads to accurate reproduction of *CO2E-HIST*. Here, to provide hints for improving the global carbon budget in C-HIST and thereby reproducing an accurate CO2 concentration in E-HIST, we focus on each model and visualize the gaps between each ESM and GCB2021 (Fig. S5). Furthermore, the discrepancies of the components of each budget between the target model and GCB2021 are depicted.

Among the ESMs, CNRM-ESM2-1 was one of the models with the best performance in reproducing *EFFC-HIST* and *CO2E-HIST*, with values that are sufficiently close to those of GCB2021 (black circle and red dot of Fig. S5). However, the detailed analysis here suggests improvements of the budget components in this model. Specifically, the cumulative land use change emission simulated by the model was only 23.5 PgC, i.e., the smallest among the analyzed models (Table 5) and much smaller (by 171.6 PgC) than the GCB2021 value (brown vector in Fig. 5S). Thus, the relatively good performance of this model in terms of *CO2E-HIST*, despite the small land use change emission, might be sustained by outgassing carbon from the ocean, which originates from the external carbon input from rivers to the ocean assumed in this model (Seferian et al., 2019).

Compared with GCB2021, MPI-ESM1-2-LR showed less discrepancies in terms of the budget components (Table 4), which are depicted by shorter vectors in Fig. S5. This model is diagnosed to have 200.8 PgC of *ELUC*, 186.5 PgC of *CLN*, and 136.3 PgC of *CO*, which differ from the GCB2021 values by only +5.8, +6.5, and −13.7 PgC, respectively. Despite the good consistency of each budget component, this model eventually overestimated the CO2 concentration by 6.8 ppmv in E-HIST and underestimated the compatible fossil fuel emission by 44 PgC in C-HIST, depicted in Fig. S5 as the gap between the current condition (black circle) and GCB2021 (red dot). This problem is likely caused by the budget imbalance found in the GCB2021 estimation, as discussed in the following.

Generally, we expect the global carbon budget to satisfy the following equation:

*EFF* + *ELUC* = (*CA* + *CO* + *CLN*),

and thus

*EFF* + *ELUC* − (*CA* + *CO* + *CLN*) = 0.

However, this does not necessarily hold strictly when applying the current estimation of GCB2021 to this equation because each budget component is estimated independently and thus the total budget closure is not assured. Now, GCB2021 has a budget imbalance of approximately 30 PgC:

*EFF* + *ELUC* − (*CA* + *CO* + *CLN*)

= 400 + 195 − (110.6\*2.124 + 150 + 180)

= 31.4 PgC.

This means GCB2021 overestimates the emission total *EFF* +*ELUC* and/or underestimates the partitioning total *CA* + *CO* + *CLN*.

As a result, even if a model can perfectly mimic *ELUC*, *CO*, and *CLN* as identical to GCB2021, such a model will overestimate the CO2 concentration in E-HIST because the budget imbalance of 31.4 PgC is imposed on *CA* as follows:

*CA = EFF* + *ELUC* − *CO* − *CLN* = 400 + 195 − 180 − 150 = 265 PgC,

which correspond to 409 ppmv at the end of the historical simulation. For the same reason, such a model should underestimate the compatible fossil fuel emission in C-HIST because *EFF* is diagnosed in C-HIST as follows:

*EFF* = *CA* + *CO* + *CLN* − *ELUC* = 235 + 180 + 150 − 195 = 370 PgC,

where the atmospheric carbon burden (235 PgC) is calculated as (397.6 ppmv − 284.3 ppmv)/2.12)). This might explain why more than half of the models, including MPI-ESM1-2-LR as mentioned above, are concentrated at the position around (*EFFC-HIST*, *CO2E-HIST*) = (370 PgC, 410 ppmv) in Fig. 5b. The gaps between the target model and GCB2021 explained by the budget imbalance are visualized in Fig. S5 as gray arrows.

Finally, it is suggested that models that plot significantly off the regression line are unlikely to adequately reproduce CO2 concentrations in E-HIST and compatible emissions in C-HIST simultaneously. The example is MIROC-ES2L, which yields lower CO2 concentration in E-HIST than that expected from the multi-model regression line (black circle in Fig. S5). The underestimation of CO2 concentration would not be resolved by just mimicking the budget components of GCB2021 (the arrowhead of the blue line), and thus the unexpectedly lower CO2 concentration of MIROC-ES2L is likely attributed to other problems, e.g., different behavior in the climate and carbon cycle processes between C-HIST and E-HIST. The same is likely true of ACCESS-ESM1-5, a model that simulates higher CO2 concentration than that expected from the multi-model regression line.

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Figure S6 Atmospheric CO2 concentration in E-driven experiments (*CO2E-HIST*) and compatible fossil fuel emission in C-driven experiments (*CFFC-HIST*). *CFFC-HIST* used here is corrected by the carbon budget imbalance found in each model (Appendix B). Circles represent the targeted model in each panel, and corresponding values of GCB2021 are shown in red. The scatter plots and regression lines are the same as in Fig. 5, and the carbon budget improvements toward the best estimate of GCB2021 are shown by arrows (brown: land use change emission, green: natural land carbon sink, and blue: ocean carbon sink. Gray arrows show the possible change when the carbon budget imbalance of GCB2021 (*IB* = *EFF* + *ELUC* − (*CL* + *CO* + *CA*) = +30 PgC) is resolved by reduction in fossil fuel emission (light gray vertical arrow) or by other means (dark gray). The solid black line represents the regression line depicted in Fig. 5, and the inclination of the arrows (except for the light gray arrow) is assumed to follow the slope of the regression line (−0.21 ppmv/PgC). Among the panels, the x- and y-axis limits are not fixed and are different for visualization purposes, but the relative sizes of the x- and y-axis and the intervals remain the same; thus, the length of the arrows can be compared directly between panels. This analysis relies on the availability of “historical,” “esm-hist,” and “hist-noLu” simulation results.

### Supplementary section S2: Analysis of feedback in the five qualitatively divided eras

In Sect. 4.2, the simulated CO2 concentration in E-HIST was assessed for five eras. Because each era has its own historical background, the analysis could provide suggestions regarding the cause of the concentration bias (e.g., the concentration bias in Era 1 is likely attributable to simulation problems in land use change emission). Here, to confirm the cause of the biases more qualitatively and quantitatively, we propose an extended analysis that quantifies the driver of change in the global carbon budgets of each era. This method is same as the analysis used for Table 5 (Appendix C) but applied to each era, not to the entire historical period.

The necessary simulation results for this analysis are (A) C-HIST, (B) C-HIST-NOLU, (C) C-HIST-BGC, and (D) C-HIST-CO2. The cumulative carbon changes of the land and ocean are expressed as the sum of four types of drivers (see Appendix C):

(1) CO2–carbon feedback (CO2-BGC),

(2) climate–carbon feedback caused by CO2-induced warming (CO2-CLIM),

(3) land use change impact (LUC),

(4) non-CO2 effects (NONCO2).

Owing to data availability, the assessment here is limited to only two models: CanESM5 and MIROC-ES2L. The results are shown in Fig. S6, where the prescribed fossil fuel emissions, simulated natural sinks, and simulated land use change emission in each of the five eras are depicted explicitly by arrows. Comparison reveals common features between the two models with regard to the ocean carbon sink. First, the magnitude of the ocean carbon sink is similar between both models, and the sink is diagnosed to be controlled mainly by CO2–carbon feedback, irrespective of the target era (blue arrows). Second, other decomposed drivers of the ocean carbon sink, i.e., CO2-CLIM, LUC and NONCO2, are diagnosed to have limited impact on ocean carbon uptake (arrows with orange, pink, and olive lines) in both models, although a previous study suggested that regional oceans experience strong impact from non-CO2 forcings (Yamamoto et al., 2022).

Meanwhile, with regard to the land carbon cycle, the two models showed distinct differences at some points. First, it is confirmed in Fig. S6 that CanESM5 is diagnosed to have a relatively low land use change emission of 12 PgC (tan arrow) in Era 1, which is approximately one-third of that of MIROC-ES2L (35 PgC). This result is in line with the fact that CanESM5 has lower CO2 growth in Era 1 (Fig. 9c).

Second, this analysis revealed that MIROC-ES2L receives a positive effect from NONCO2 in terms of land carbon uptake (purple arrow), particularly in Era 4; NONCO2 promoted land carbon accumulation by 30 PgC. Meanwhile, CanESM5 is diagnosed to receive a negative effect from NONCO2 in the corresponding era, i.e., terrestrial carbon is reduced by 30 PgC. Consequently, the discrepancy of the NONCO2 effect between the two models amounts to 60 PgC in Era 4 alone. The analysis strongly suggests that MIROC-ES2L has problems in terms of land carbon uptake in response to NONCO2, given that this model showed the lowest rate of growth of CO2 in this era (Fig. 9c).

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Figure S7 Water flow diagram of global carbon budget simulated by two CMIP6 ESMs (upper: CanESM5, lower: MIROC-ES2L). This analysis depends on the availability of four types of C-driven experiment (Tables 1 and 2). The historical period (1850–2014) was divided into the same five eras as used in Fig. 9, and the flux components in the cumulative values are shown by arrows and numbers (positive means carbon input into the atmosphere). Fossil fuel emission (gray) was obtained from the CMIP6 prescribed data. Changes in natural carbon fluxes were further decomposed into four drivers: (1) CO2–carbon feedback (CO2-BGC, green and blue), (2) climate–carbon feedback induced by CO2 (CO2-CLIM, red and magenta), (3) land use change effect (LUC, tan and olive), and (4) non-CO2 effects (NONCO2, purple and pink), as in Table 2. Black arrows show the increase in atmospheric carbon (PgC) with the concentration change in parentheses (ppmv), calculated as the residual of the other carbon budgets in the C-driven experiments.