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Asymmetry in carbon cycle feedbacks and transient climate response under positive and negative CO_2 emissions

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Supplement

S1. Contribution Frameworks

S1.1 Land Concentration-carbon Feedback Decomposition Contribution Framework

Following from Section 2.3.2, the asymmetry in the concentration-carbon feedback can be determined by taking the first derivative as follows:

$$
\begin{aligned}
[1]\ \Delta\beta_{\mathrm{L}} &= \mathrm{CUE}_{\Delta}\frac{\Delta GPP^{BGC}}{\Delta \mathrm{C_A}}\Delta\tau_{cveg\Delta} + \tau_{cveg\Delta}\frac{\Delta GPP^{BGC}}{\Delta \mathrm{C_A}}\Delta\mathrm{CUE}_{\Delta} + \tau_{cveg\Delta}\mathrm{CUE}_{\Delta}\Delta\frac{\Delta GPP^{BGC}}{\Delta \mathrm{C_A}} + \frac{\Delta R_h^{BGC}}{\Delta LF^{BGC}}\frac{\Delta LF^{BGC}}{\Delta \mathrm{C_A}}\Delta\tau_{csoil\Delta} \\
&\quad + \tau_{csoil\Delta}\frac{\Delta LF^{BGC}}{\Delta \mathrm{C_A}}\Delta\frac{\Delta R_h^{BGC}}{\Delta LF^{BGC}} + \tau_{csoil\Delta}\frac{\Delta R_h^{BGC}}{\Delta LF^{BGC}}\Delta\frac{\Delta LF^{BGC}}{\Delta \mathrm{C_A}} \\
&= \frac{\Delta NPP^{BGC}}{\Delta GPP^{BGC}}\frac{\Delta GPP^{BGC}}{\Delta \mathrm{C_A}}\Delta\frac{\Delta C_V^{BGC}}{\Delta NPP^{BGC}} + \frac{\Delta C_V^{BGC}}{\Delta NPP^{BGC}}\frac{\Delta GPP^{BGC}}{\Delta \mathrm{C_A}}\Delta\frac{\Delta NPP^{BGC}}{\Delta GPP^{BGC}} + \frac{\Delta C_V^{BGC}}{\Delta NPP^{BGC}}\frac{\Delta NPP^{BGC}}{\Delta GPP^{BGC}}\Delta\frac{\Delta GPP^{BGC}}{\Delta \mathrm{C_A}} \\
&\quad + \frac{\Delta R_h^{BGC}}{\Delta LF^{BGC}}\frac{\Delta LF^{BGC}}{\Delta \mathrm{C_A}}\Delta\frac{\Delta C_S^{BGC}}{\Delta R_h^{BGC}} + \frac{\Delta C_S^{BGC}}{\Delta R_h^{BGC}}\frac{\Delta LF^{BGC}}{\Delta \mathrm{C_A}}\Delta\frac{\Delta R_h^{BGC}}{\Delta LF^{BGC}} + \frac{\Delta C_S^{BGC}}{\Delta R_h^{BGC}}\frac{\Delta R_h^{BGC}}{\Delta LF^{BGC}}\Delta\frac{\Delta LF^{BGC}}{\Delta \mathrm{C_A}}
\end{aligned}
$$

The last part of each term is the asymmetry (difference under positive and negative emissions) and the rest of the terms are taken from the negative emissions simulation. The percentage contribution of each term can then be determined as $\frac{X}{\Delta\beta_{\mathrm{L}}}$ x 100, where 'X' denotes any of the six terms above.

S1.2 Transient Climate Response to Cumulative CO_2 Emissions (TCRE) Contribution Framework

To determine the contribution of the airborne/removal fraction, climate sensitivity and respective carbon cycle feedbacks to the asymmetry in the TCRE, the first derivative of equation [12] in Section 2.3.3 as follows:

$$\Delta TCRE = \frac{AF^4}{k^2}\left[(k+\beta)\Delta\alpha - \alpha\Delta\beta - \alpha^2\Delta\gamma\right]$$

The last part of each term is the asymmetry (difference under positive and negative emissions) and the rest of the terms are taken from the negative emissions simulation.

S2. Figures and Tables

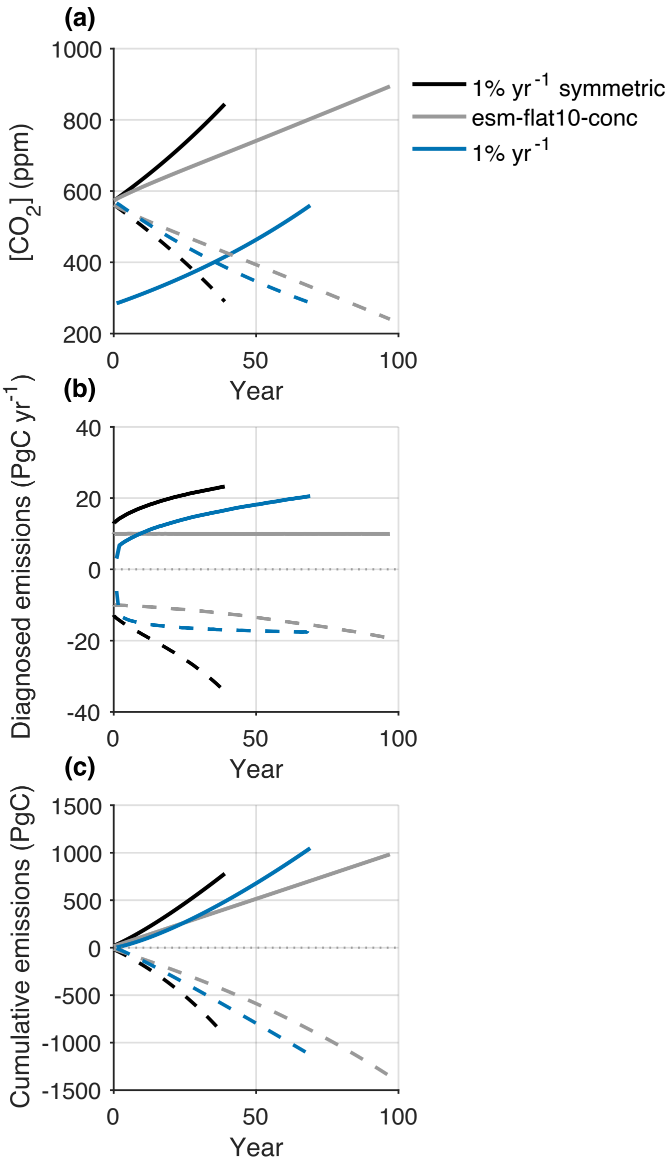

Figure S1. Prescribed atmospheric CO_2 concentration, b. diagnosed annual positive and negative CO_2 emissions, and c. diagnosed cumulative positive and negative CO_2 emissions in the fully coupled mode for all simulations. Solid lines represent the positive emissions run; dashed lines represent the negative emissions run.

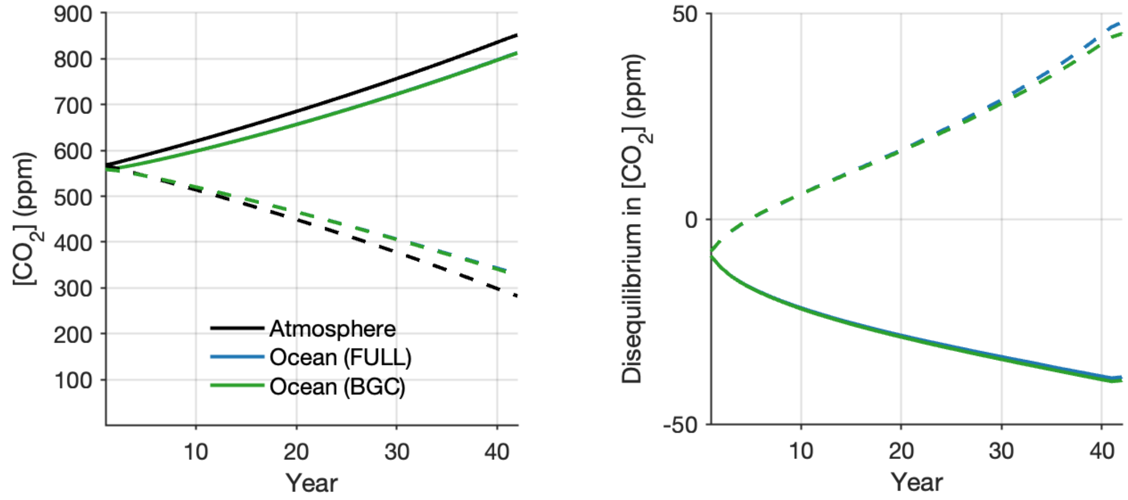

Figure S2. Atmospheric CO_2 concentration and partial pressure of CO_2 in surface ocean and disequilibrium in the CO_2 concentration between the atmosphere and ocean in the 1% yr^{-1} symmetric simulations. The disequilibrium is computed as: ocean partial pressure of CO_2 – atmosphere partial pressure of CO_2. Fully coupled (FULL); biogeochemically coupled (BGC). Solid lines represent the positive emissions run; dashed lines represent the negative emissions run.

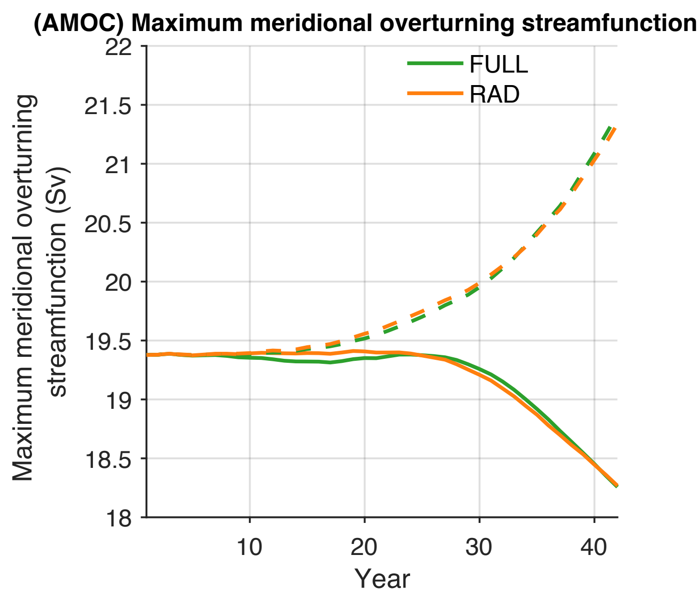

Figure S3. Atlantic meridional overturning circulation in the 1% yr^{-1} symmetric simulations. Fully coupled (FULL); biogeochemically coupled (BGC). Solid lines represent the positive emissions run; dashed lines represent the negative emissions run.

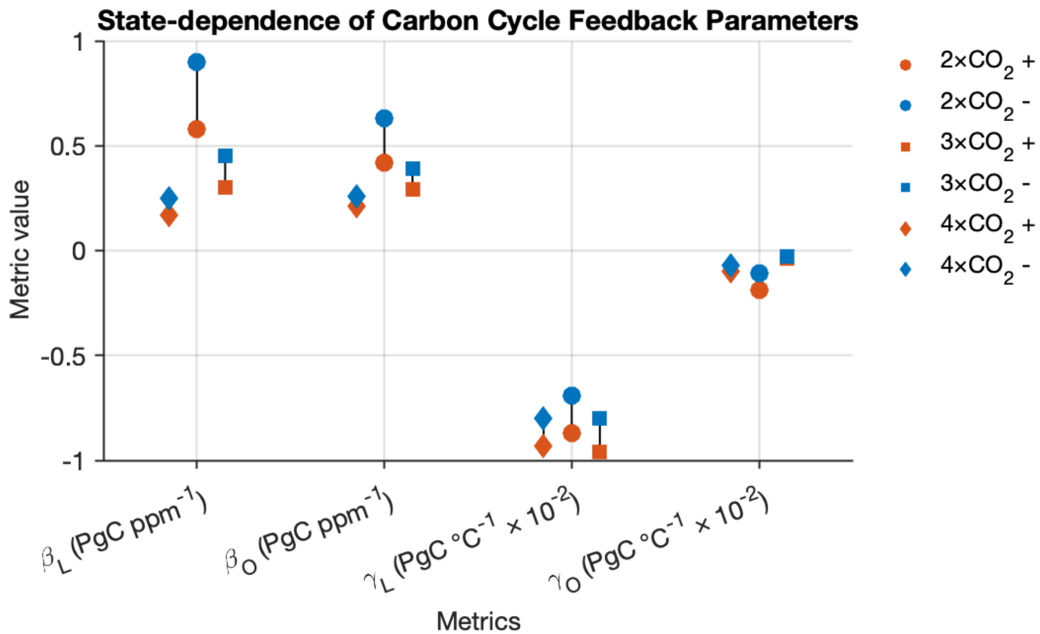

Figure S4. State-dependence of carbon cycle feedback parameter asymmetry under several equilibrium states in the 1% yr^{-1} symmetric simulations. Each symbol represents the magnitude of each feedback under positive (+) and negative (-) emissions for 2xCO_2, 3xCO_2 and 4xCO_2 equilibrium states.

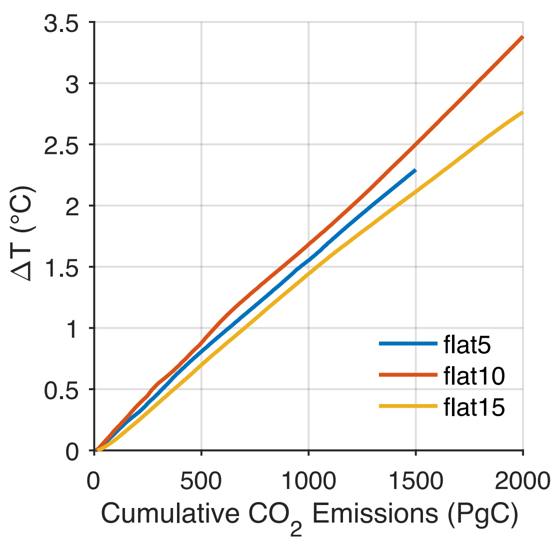

Figure S5. Transient climate response to cumulative CO_2 emissions (TCRE) in a 2xCO_2 equilibrium state: All simulations shown are emissions-driven. Flat5 = emissions of 5 PgC yr^{-1}; Flat10 = emissions of 10 PgC yr^{-1}; Flat15 = emissions of 15 PgC yr^{-1}.

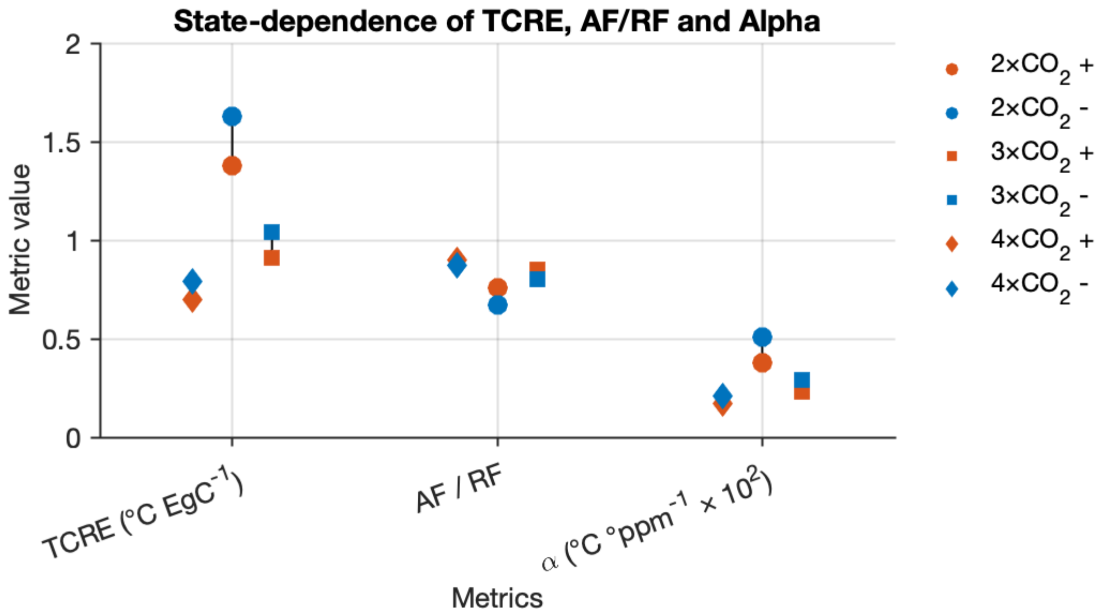

Figure S6. State-dependence of transient climate response to cumulative CO_2 emissions (TCRE), airborne and removal fraction (AF/RF) and climate sensitivity (alpha) under several equilibrium states in the 1% yr^{-1} symmetric simulations. Each symbol represents the magnitude of each metric under positive (+) and negative (-) emissions for 2xCO_2, 3xCO_2 and 4xCO_2 equilibrium states.

Table S1: Decomposition of the land concentration-carbon feedback parameter in the 1% yr^{-1} symmetric positive and negative emissions runs quantified at the end of each simulation. The sensitivity of vegetation carbon to changes in CO_2 concentration is decomposed to the residence time of vegetation carbon, the carbon use efficiency (proportion of GPP that is turned into NPP) and a measure of the CO_2 fertilization effect. The sensitivity of soil carbon to changes in CO_2 concentration is decomposed to the residence time of soil carbon, the change in the soil respiration rate per unit change in leaf litter flux, and the sensitivity of the leaf litter flux to changes in CO_2 concentration. The last column shows the percentage contribution of each term to the asymmetry in the land concentration-carbon feedback parameter. Note that the fifth term (change in the soil respiration rate per unit change in leaf litter flux) is negative as its asymmetry decreases, leading to a decrease in the asymmetry in the land concentration-carbon feedback parameter.

	Positive Emissions	***Negative Emissions***	% ***Contribution***
Vegetation carbon residence time (yr)	3.3	3.89	15
Carbon use efficiency	0.62	0.65	5
CO_2 fertilization effect (PgC/yr/ppm)	0.09	0.14	36
Soil carbon residence time (yr)	11.4	12.5	14

Soil respiration / leaf litter	0.7	0.64	-15
Leaf litter / CO_2 (PgC/yr/ppm)	0.05	0.07	45