Supplementary Information: Testing GWP* to quantify non-CO_2 contributions in the carbon budget framework in overshoot scenarios

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Table S1 Performance of the GWP100 and GWP* metrics for reproducing the temperature pathways under the six SSP scenarios when the metrics are used to convert CH_4 emissions to CO_2-eq emissions. The root mean square error (RMSE) indicates the deviation of the temperature pathway calculated from CO_2-eq emissions using the IRF from the temperature pathway directly calculated from CH_4 emissions. RMSE is shown for each metric and for two different periods: 1750-2100 and 1750-2300.

Scenario	**RMSE**$_{GWP100}$ 1750-2100	**RMSE**$_{GWP*}$ 1750-2100	**RMSE**$_{GWP100}$ 1750-2300	**RMSE**$_{GWP*}$ 1750-2300
SSP1-1.9	4.69	1.14	19.95	3.24
SSP1-2.6	4.5	1.06	20.82	3.32
SSP4-3.4	3.4	0.85	30.32	4.43
SSP4-6.0	3.77	0.98	35.36	4.95
SSP5-3.4-OS	5.1	1.59	22.73	3.83
SSP5-8.5	3.99	1.11	36.63	5.03

Table S2 ESMs used for the ACC2 emulation (from Table 1 in Melnikova et. al, 2021)

ESM	**IPSL-CM6A-LR**	**CNRM-ESM2-1**	**CanESM5**	**UKESM1-0-LL**	**MIROC-ES2L**
Reference	(Boucher et al., 2020)	(Séférian et al., 2019)	(Swart et al., 2019)	(Sellar et al., 2019)	(Hajima et al., 2020)
SSP5-3.4-OS period	2040–2300	2015–2300	2040–2300	2040–2300	2015–2100
Land carbon	ORCHIDEE, br.2.0	ISBA-CTRIP	CLASS-CTEM	JULES-ES-1.0	VISIT-e
Nitrogen cycle	No	Implicit	No	Yes	Yes
Permafrost	No	No	No	No	No
Fires	No	Yes (natural)	No	No	No
Dynamic vegetation	No	No	dynamic wetlands	Yes	No
Ocean carbon	PISCES-v2	PISCESv2-gas	CMOC	MEDUSA-2.1	OECO2
Data set DOIs***	https://doi.org/10.22033/ESGF/CMIP6.5251	https://doi.org/10.22033/ESGF/CMIP6.4165	https://doi.org/10.22033/ESGF/CMIP6.3673	https://doi.org/10.22033/ESGF/CMIP6.6298	https://doi.org/10.22033/ESGF/CMIP6.5710
	https://doi.org/10.22033/ESGF/CMIP6.5195	https://doi.org/10.22033/ESGF/CMIP6.4068	https://doi.org/10.22033/ESGF/CMIP6.3610	https://doi.org/10.22033/ESGF/CMIP6.6113	https://doi.org/10.22033/ESGF/CMIP6.5602
	https://doi.org/10.22033/ESGF/CMIP6.5271	https://doi.org/10.22033/ESGF/CMIP6.4221	https://doi.org/10.22033/ESGF/CMIP6.3696	https://doi.org/10.22033/ESGF/CMIP6.6405	https://doi.org/10.22033/ESGF/CMIP6.5767
	https://doi.org/10.22033/ESGF/CMIP6.5269	https://doi.org/10.22033/ESGF/CMIP6.4047	https://doi.org/10.22033/ESGF/CMIP6.3694	https://doi.org/10.22033/ESGF/CMIP6.6397	https://doi.org/10.22033/ESGF/CMIP6.5582
		https://doi.org/10.22033/ESGF/CMIP6.4223	https://doi.org/10.22033/ESGF/CMIP6.3600	https://doi.org/10.22033/ESGF/CMIP6.6055	https://doi.org/10.22033/ESGF/CMIP6.5769
			https://doi.org/10.22033/ESGF/CMIP6.3697	https://doi.org/10.22033/ESGF/CMIP6.6409	https://doi.org/10.22033/ESGF/CMIP6.5512
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				https://doi.org/10.22033/ESGF/CMIP6.5929	
				https://doi.org/10.22033/ESGF/CMIP6.5969	

Table S3 Parameter ranges considered in ACC2 emulations

ACC2 Parameter	Definition	Values
ECS	Equilibrium climate sensitivity	2.0 to 5.6 with intervals of 0.2
BETA	CO_2 fertilization effect on photosynthesis	0.1 to 1.0 with intervals of 0.1
Q10	Temperature effect on heterotrophic respiration	0.7 to 2.0 with intervals of 0.1

Table S4 Best estimates of the three main parameters in ACC2 to emulate ESMs. ECS values of ESM from Zelinka *et al.* (2020) are shown for comparison.

ESM	Ensemble member (COU)	Ensemble member (BGC)	ECS Zelinka et al. (2020)	ACC2 ECS	ACC2 BETA	ACC2 Q10
CanESM5	r1i1p1f1	r1i1p2f1	5.64	4.8	0.6	1.1
CNRM-ESM2-1	r1i1p1f2	r1i1p1f2	4.79	3.8	0.9	1.3
IPSL-CM6A-LR	r1i1p1f1	r1i1p1f1	4.56	4.0	0.6	1.2
MIROC-ES2L	r1i1p1f2	r1i1p1f2	2.66	2.4	0.9	2.0
UKESM1-0-LL	r4i1p1f2	r4i1p1f2	5.36	4.8	0.7	1.5

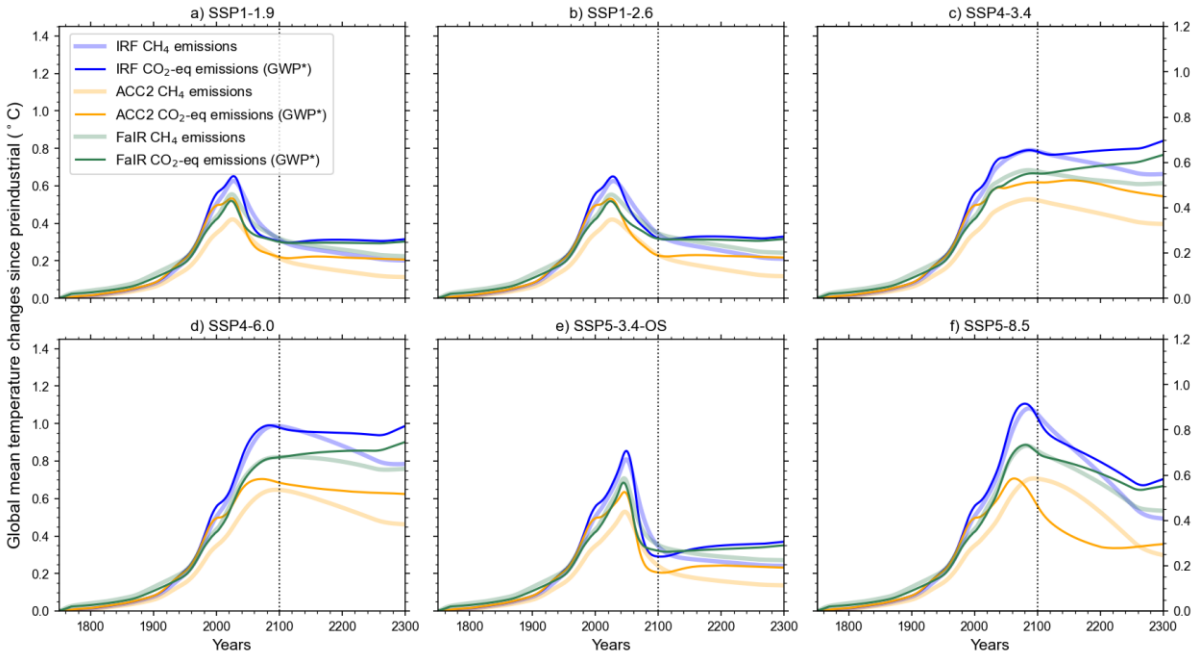

Figure S1 Intercomparison of the IRF, ACC2, and FaIR simulating the CH_4 emissions and the corresponding CO_2-eq emissions (GWP*) in the SSP scenarios. Panels a) to f) show different SSP scenarios. Lighter lines represent the temperature responses directly calculated from CH_4 emissions using the IRF, ACC2 and FaIR models. Darker lines represent the temperature responses calculated from the CO_2-eq emissions (converted from CH_4 emissions using GWP*) also using the IRF, ACC2 and FaIR models.

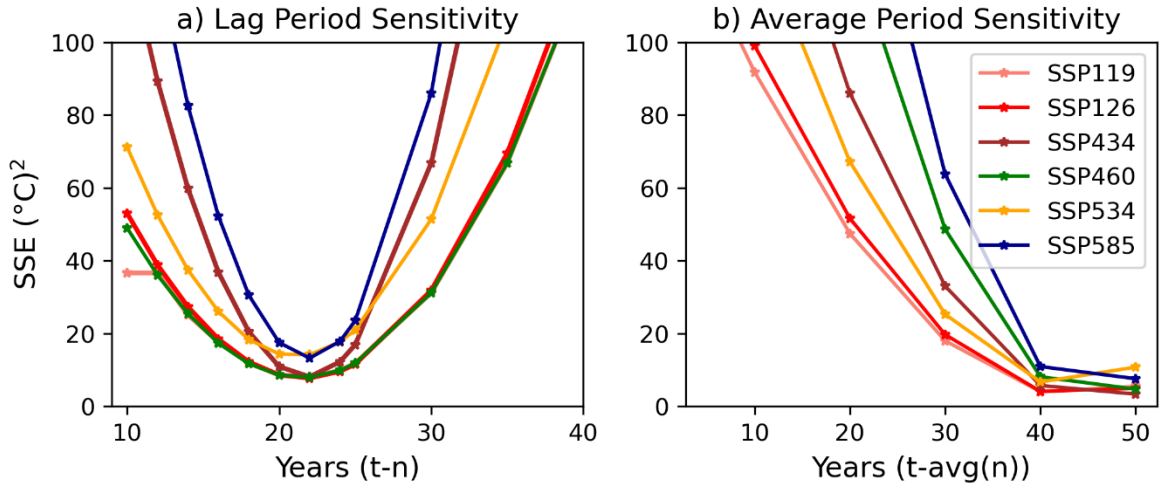

Figure S2 Sensitivity of the temperature equivalency to the parameters used to define GWP* under six SSP scenarios. Panel a) shows the relationship between the time interval of CH_4 emissions at two points in time in the GWP* flow term (20 years in default, t-n) and the goodness of fit (Sum of Square Error, SSE, y-axis) of the resulting temperature projection relative to the original projection calculated with the Impulse Response Function model directly from CH_4 emissions without using a metric. Panel b) shows the relationship between the number of years averaged to calculate the emission trend in the flow term and the goodness of fit (Sum of Square Error, SEE, y-axis) of the temperature projection relative to the original (t-avg(n)).

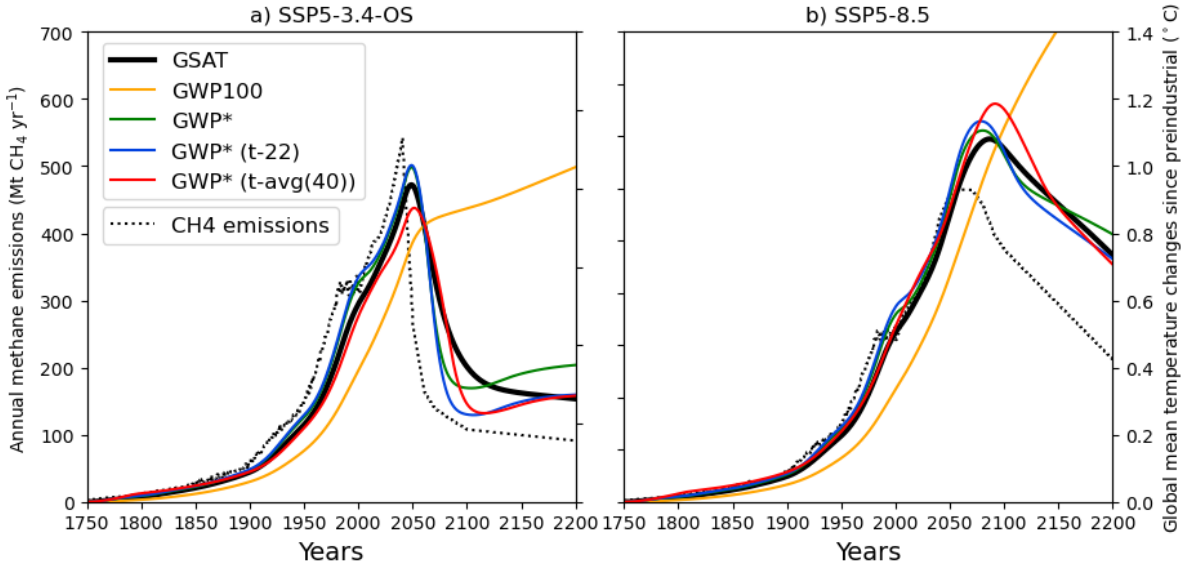

Figure S3 Temperature equivalency of using GWP* and its variants under SSP5-3.4-OS and SSP5--8.5. GWP* (t-22) is our modified GWP* with the time interval of 22 years (best estimate from Figure 2 panel a) instead of 20 years. GWP* (avg) is another modified GWP*, in which the flow term uses the average change in emissions over the past 40 years (as done in Figure S2, panel b). Panels a) and b) present the outcome under SSP5-3.4-OS and SSP5-8.5, respectively.

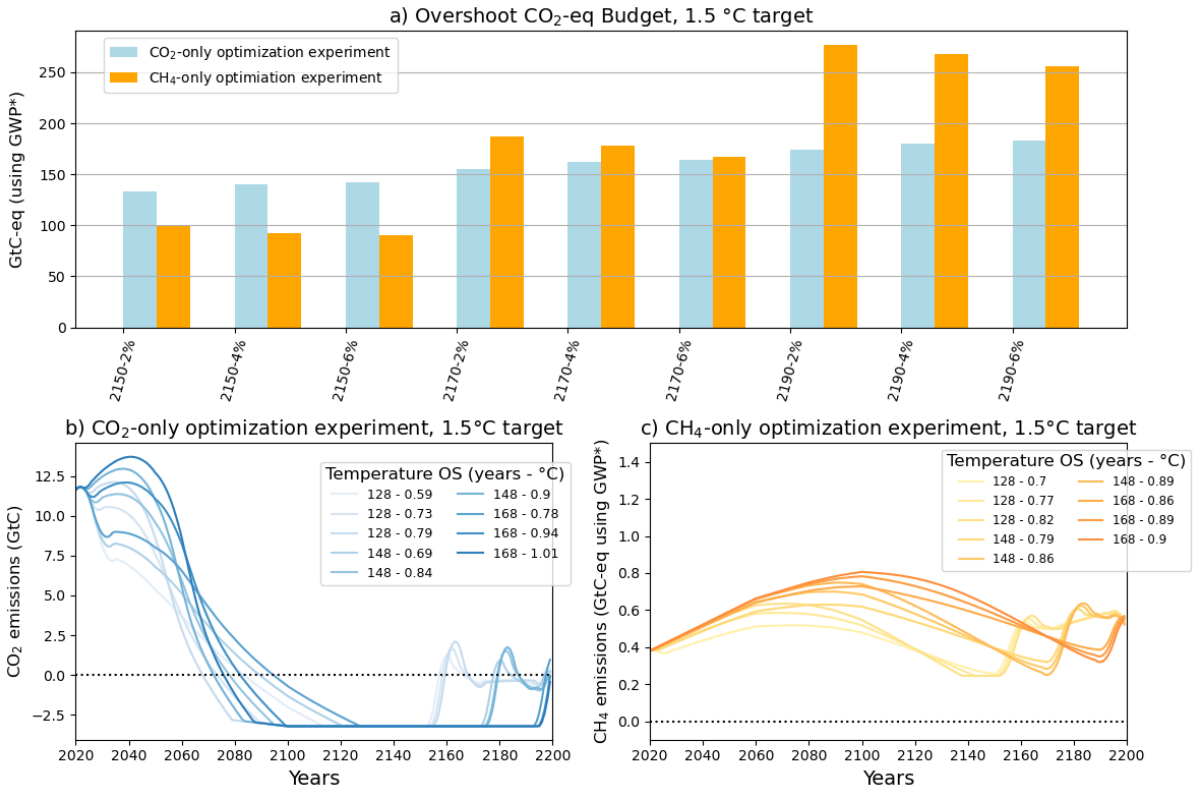

Figure S4 Overshoot CO_2-eq budgets of the 1.5 °C pathways with temperature overshoot of varying lengths and magnitudes simulated by ACC2 emulating CNRM-ESM2-1 (single-gas optimization experiments). Panel a) shows the overshoot CO_2-eq budget. The overshoot CO_2-eq budgets for the CO_2-only optimization experiment represent contributions from CO_2. Similarly, those for the CH_4-only optimization experiment represent contributions from CH_4. Panels b) and c) show the emissions pathways of CO_2 and CH_4, respectively. Legends in panels b) and c) represent the duration (years) and magnitude (°C) of temperature overshoot relative to the CO_2-only optimization experiment and CH_4-only optimization experiment.

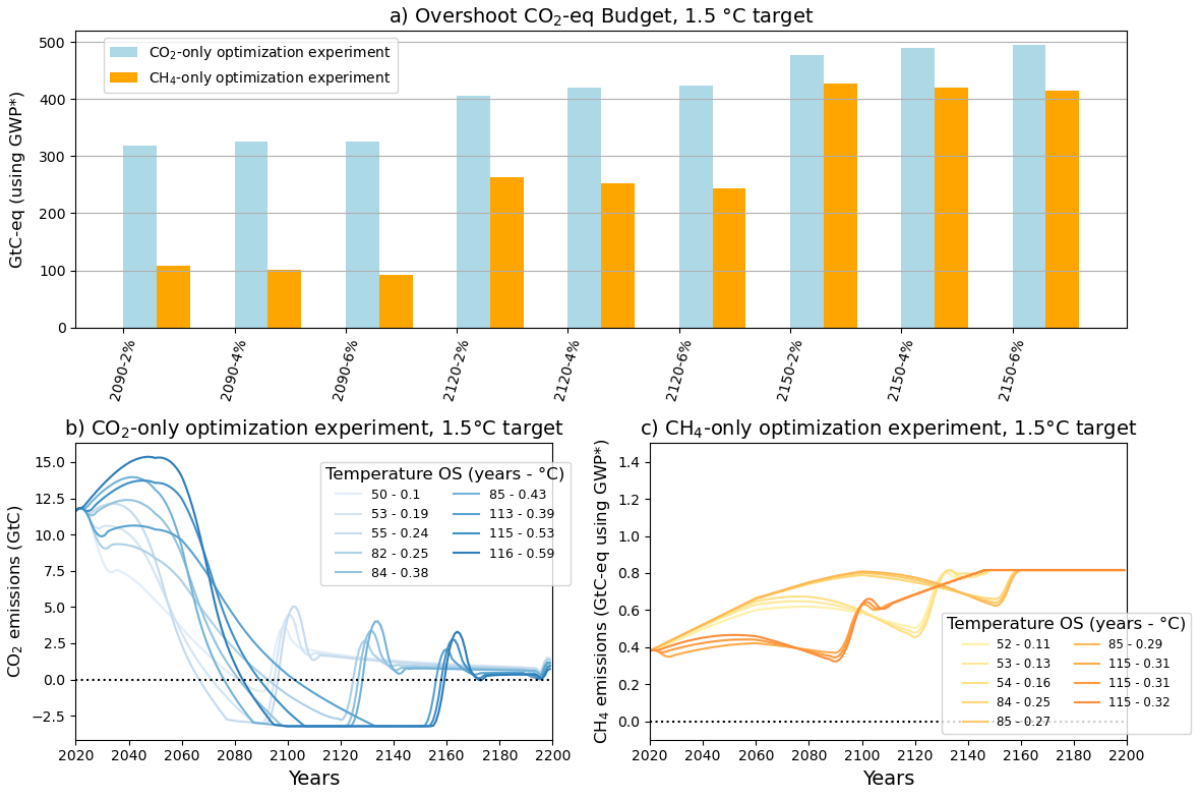

Figure S5 Overshoot CO_2-eq budgets of the 1.5 °C pathways with temperature overshoot of varying lengths and magnitudes simulated by ACC2 emulating MIROC-ES2L (single-gas optimization experiments). Panel a) shows the overshoot CO_2-eq budget. The overshoot CO_2-eq budgets for the CO_2-only optimization experiment represent contributions from CO_2. Similarly, those for the CH_4-only optimization experiment represent contributions from CH_4. Panels b) and c) show the emissions pathways of CO_2 and CH_4, respectively. Legends in panels b) and c) represent the duration (years) and magnitude (°C) of temperature overshoot relative to the CO_2-only optimization experiment and CH_4-only optimization experiment.

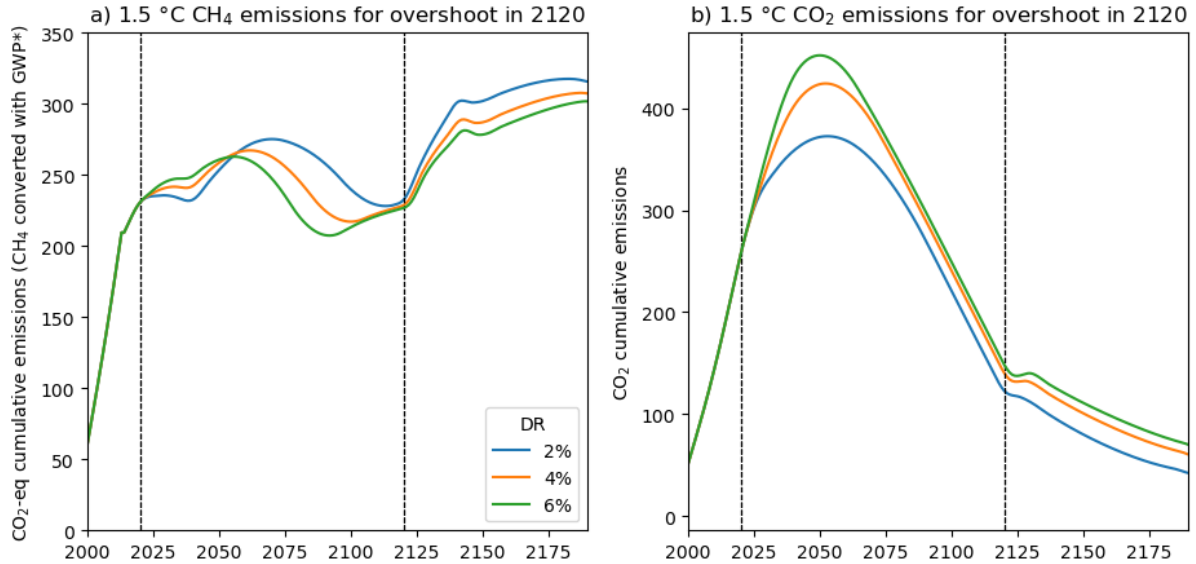

Figure S6 CH_4 and CO_2 emission pathways for scenarios towards the 1.5 °C target with overshoot till 2120 calculated with ACC2 emulating IPSL-CM6A-LR. Panel a) shows CO_2-eq cumulative emissions (from CH_4 emissions converted with GWP*), whereas panel b) shows the CO_2 cumulative emissions for meeting the 1.5 °C target in 2120, for the three discount rates considered. Vertical dashed black lines represent the start (2020) and the end (2120) of the period in which the overshoot CO_2-eq budget is calculated. These emissions are used to calculate the overshoot CO_2-eq budgets for the target year 2120 as reported in panel a) of Figure 2.

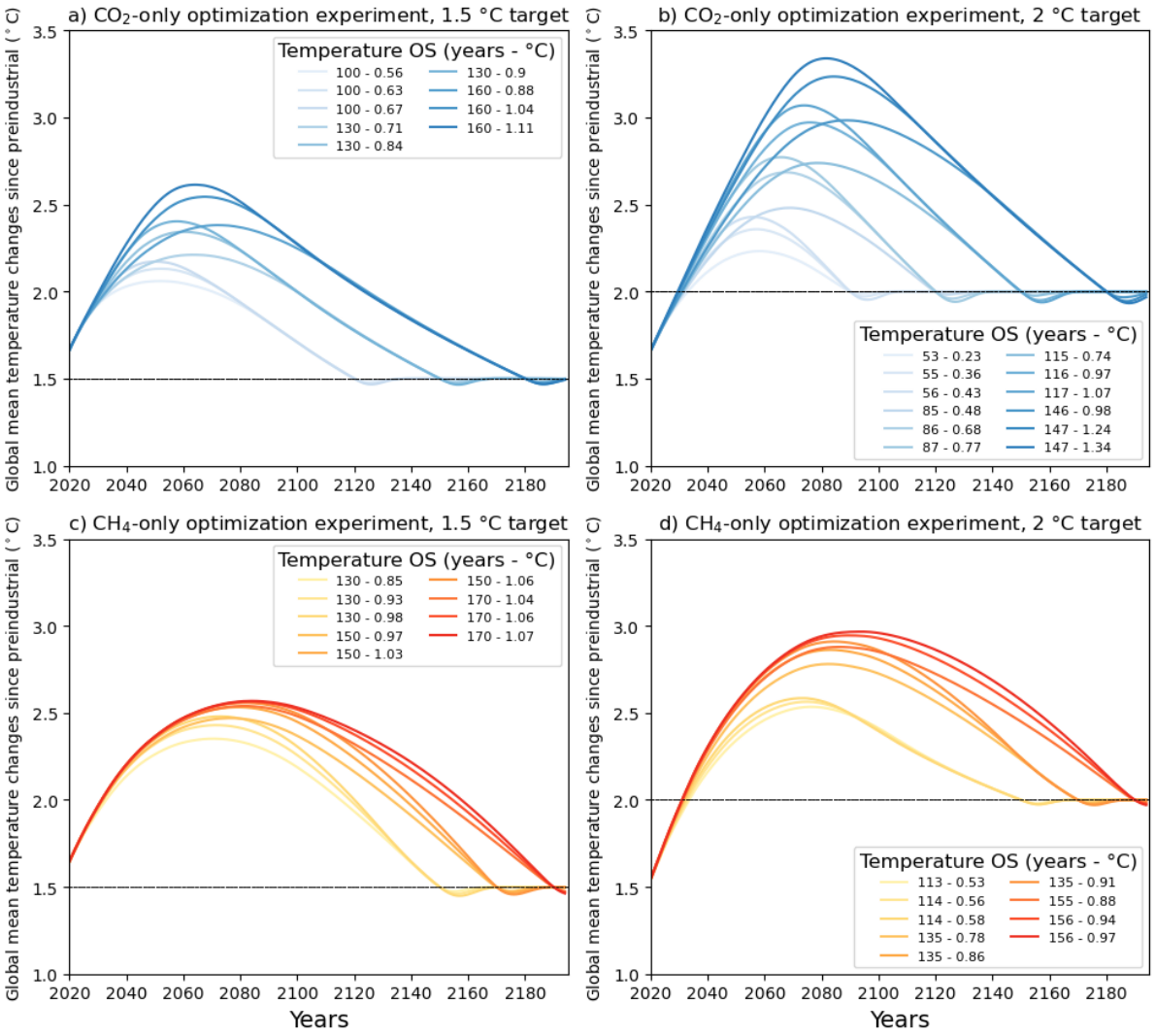

Figure S7 Temperature pathways of the CO_2-only and CH_4-only experiments towards the 1.5 °C and 2 °C target levels calculated with ACC2 emulating IPSL-CM6A-LR. Panel a) and b) show the temperature pathways for CO_2-only experiments towards the 1.5 and 2 °C target levels, whereas panel c) and d) show the temperature pathways for CH_4-only experiments towards the 1.5 and 2°C target levels. Legends represent the duration (years) and magnitude (°C) of temperature overshoot relative to the 1.5 °C or 2 °C target level.

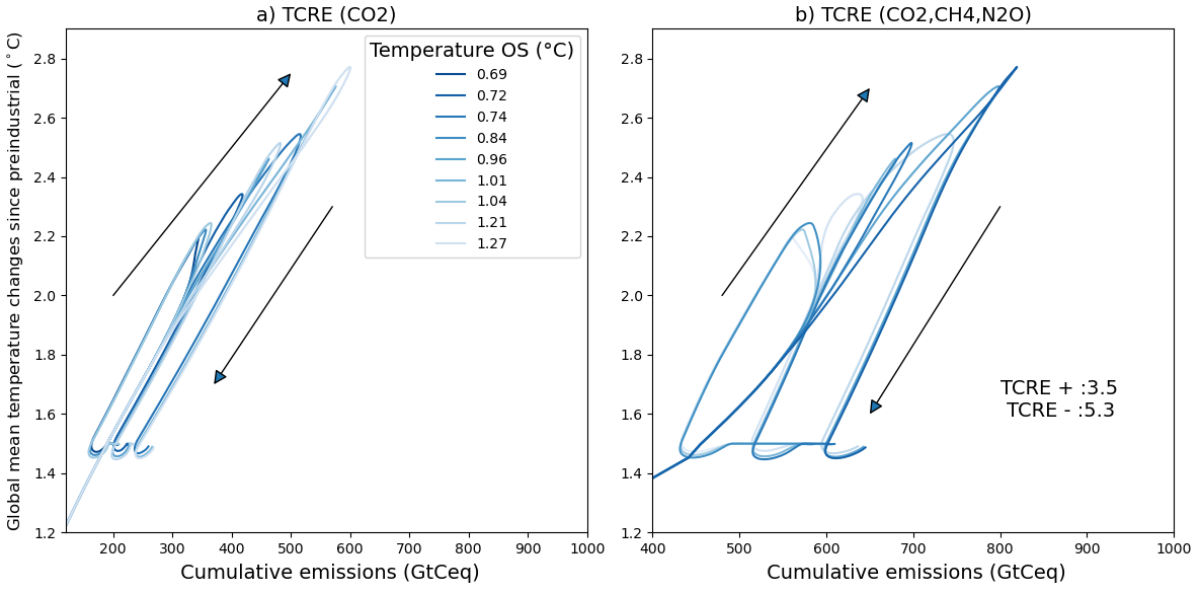

Figure S8 TCRE results for 1.5 °C target and CO_2 simulations with low CO_2 fertilization. The BETA factor is assumed to be 0.3, which is lower than the estimate of 0.6 used in ACC2 emulating IPSL-CM6A-LR (Table S4). As a consequence of the reduced CO_2 fertilization, TCRE- and TCRE+ values are different, therefore impacting the overshoot CO_2-eq budget.

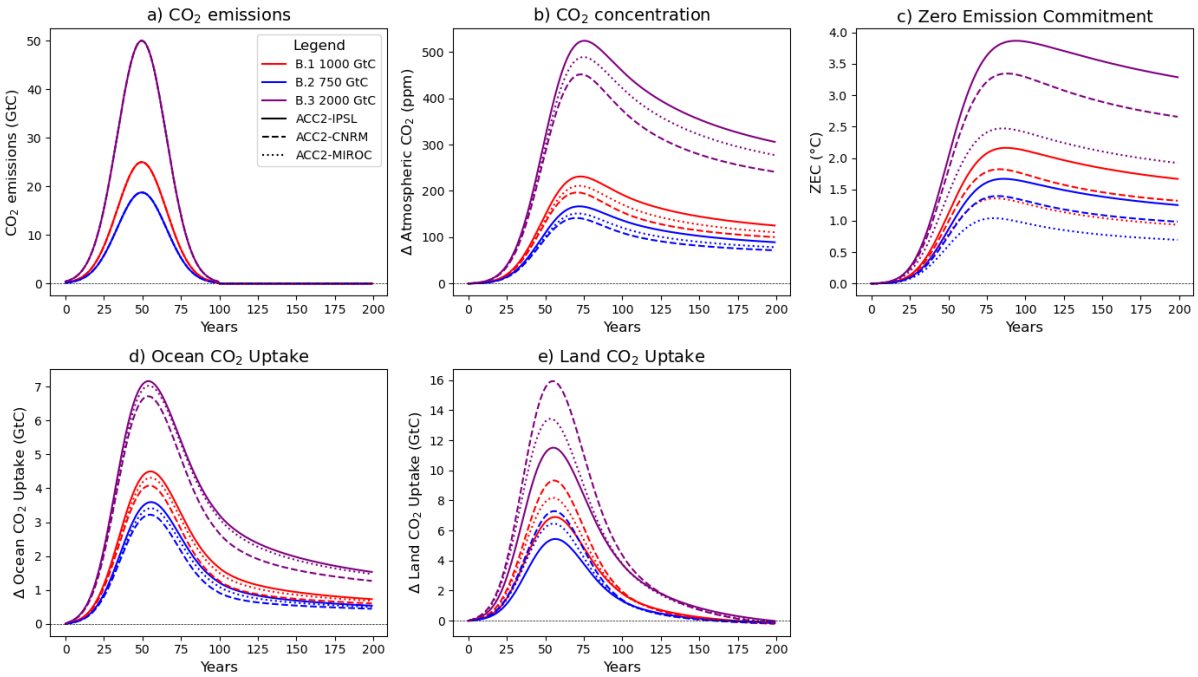

Figure S9 Results of ZECMIP-B experiments derived from ACC2 emulating IPSL-CM6A-LR, CNRM-ESM2-1 and MIROC-ES2L. Panel a) shows gaussian-shaped CO_2 pathways for different magnitude of cumulative emissions used in the ZECMIP-B experiment. Panels b) and c) show the evolution of atmospheric CO_2 concentrations and temperature, while panels d) and e) display the pathways of ocean and land CO_2 uptake. Solid, dashed and dotted lines refer to the ACC2 version emulating IPSL-CM6A-LR, CNRM-ESM2-1 and MIROC-ES2L respectively. Details of the experiments can be found in MacDougall et al., (2020).

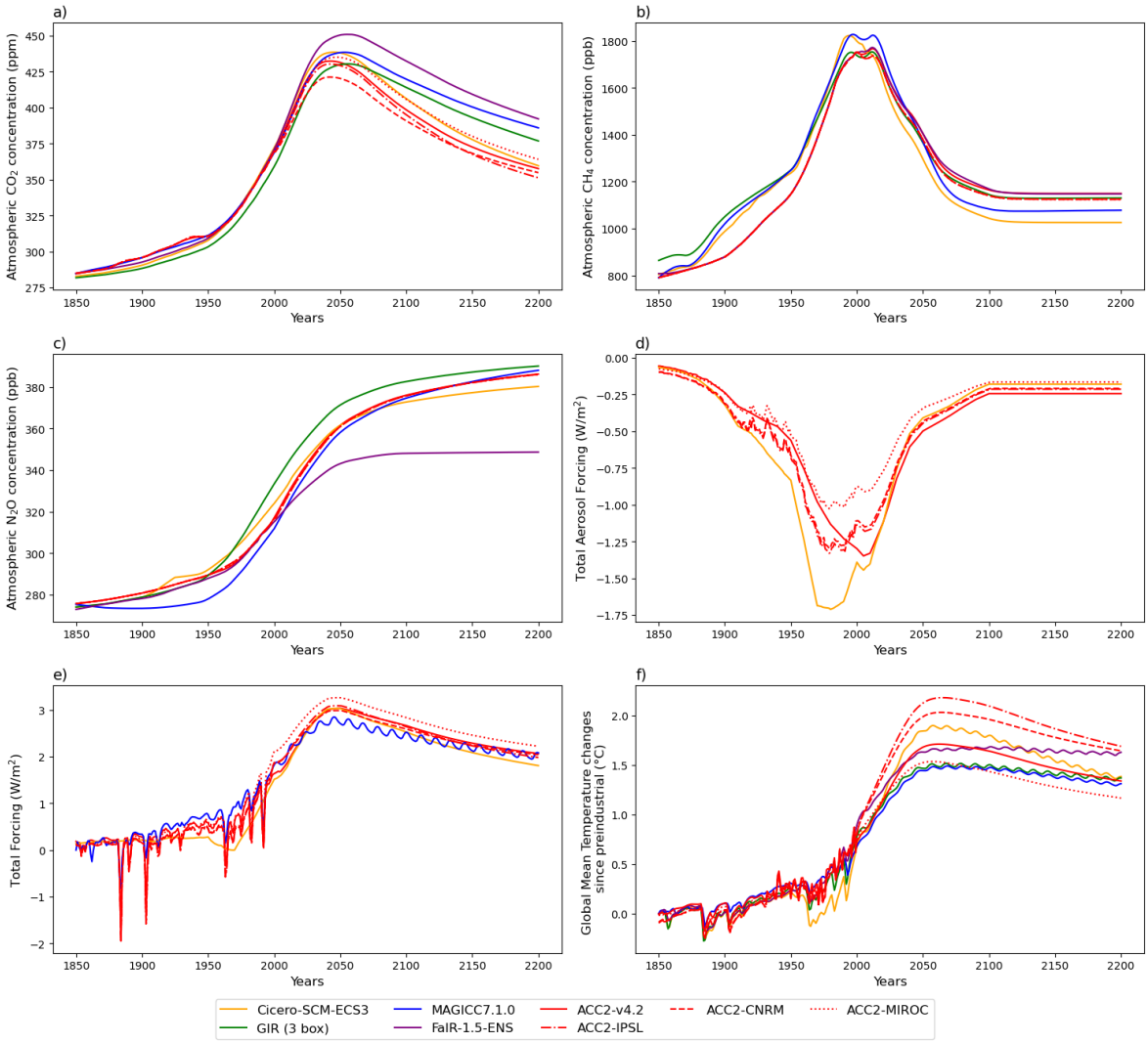

Figure S10 Emission-driven simulations performed by climate emulators using RCP2.6. Data are from Nicholls et al. (2020). Results from GHG emission-driven runs are available from the following emulators as presented: CICERO-SCM-ECS3, GIR (3 box), MAGICC7.1.0, FaIR-1.5-ENS, and ACC2 v4.2. ACC2 also contributes with the three versions emulating IPSL-CM6A-LR, CNRM-ESM2-1 and MIROC-ES2L. Only available models are shown for each of the following variables: atmospheric CO_2, CH_4, and N_2O concentrations (ppm, ppb, ppb, respectively), total aerosol forcing (W/m2), total forcing (W/m2), and global temperature changes (°C) (panels a to f, respectively). The number of models shown for the radiative forcing terms (panels d and e) is limited because some models report only effective radiative forcing. The temperature data were adjusted for the 1850-1900 reference.

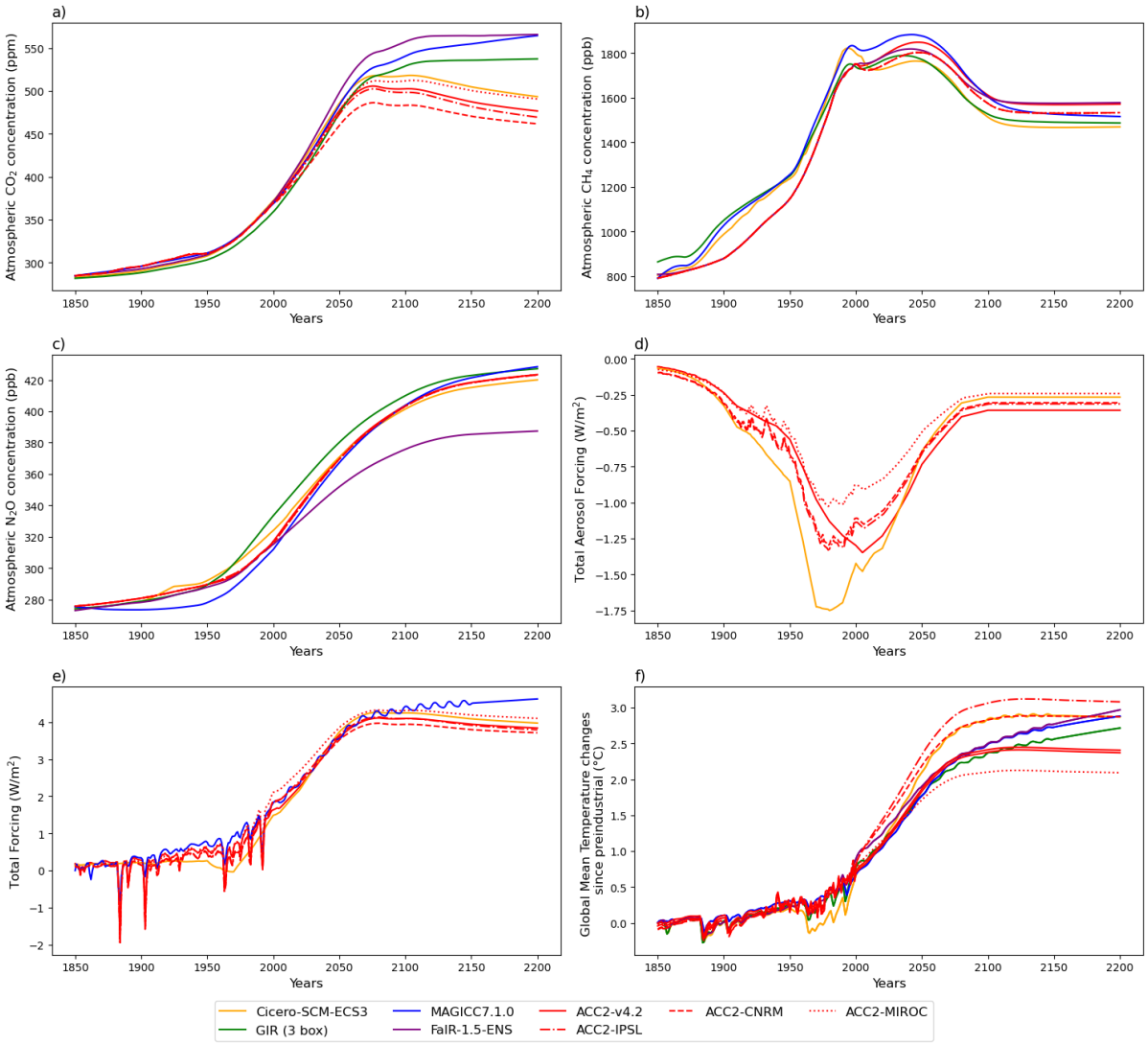

Figure S11 Emission-driven simulations performed by climate emulators using RCP4.5. Data are from Nicholls et al. (2020). Results from GHG emission-driven runs are available from the following emulators as presented: CICERO-SCM-ECS3, GIR (3 box), MAGICC7.1.0, FaIR-1.5-ENS, and ACC2 v4.2. ACC2 also contributes with the three versions emulating IPSL-CM6A-LR, CNRM-ESM2-1 and MIROC-ES2L. Only available models are shown for each of the following variables: atmospheric CO2, CH4, and N2O concentrations (ppm, ppb, ppb, respectively), total aerosol forcing (W/m2), total forcing (W/m2), and global temperature changes (°C) (panels a to f, respectively). The number of models shown for the radiative forcing terms (panels d and e) is limited because some models report only effective radiative forcing. The temperature data were adjusted for the 1850-1900 reference.

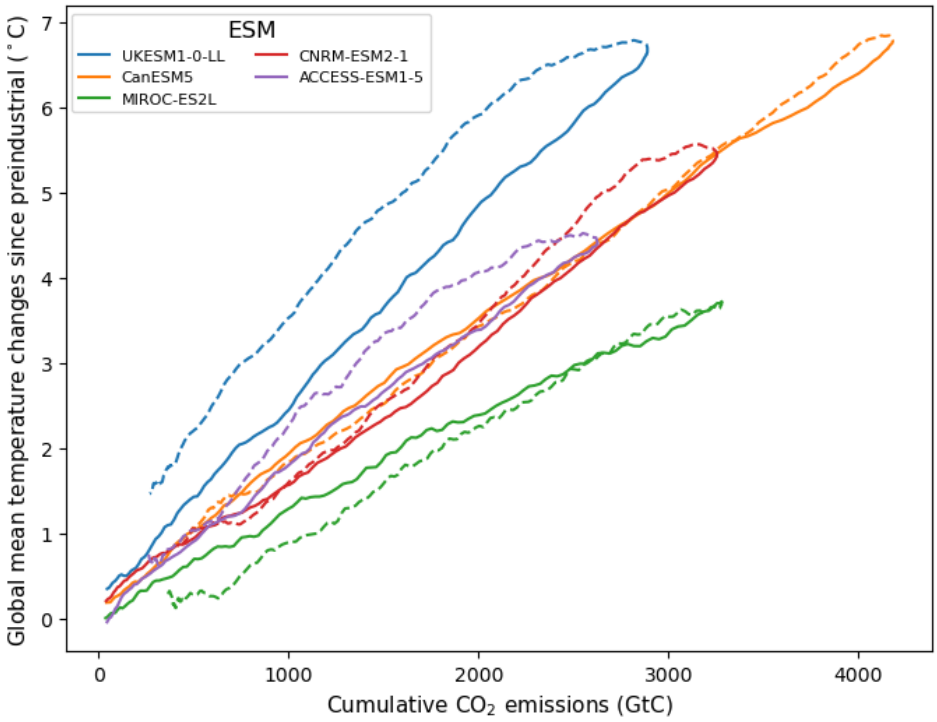

Figure S12 TCRE results for the 1pctCO2-cdr simulation (Keller et al., 2018) experiments for different ESMs deriving from the CMIP6 project. Data were obtained from ESGF repositories (e.g. https://aims2.llnl.gov/search/cmip6/).

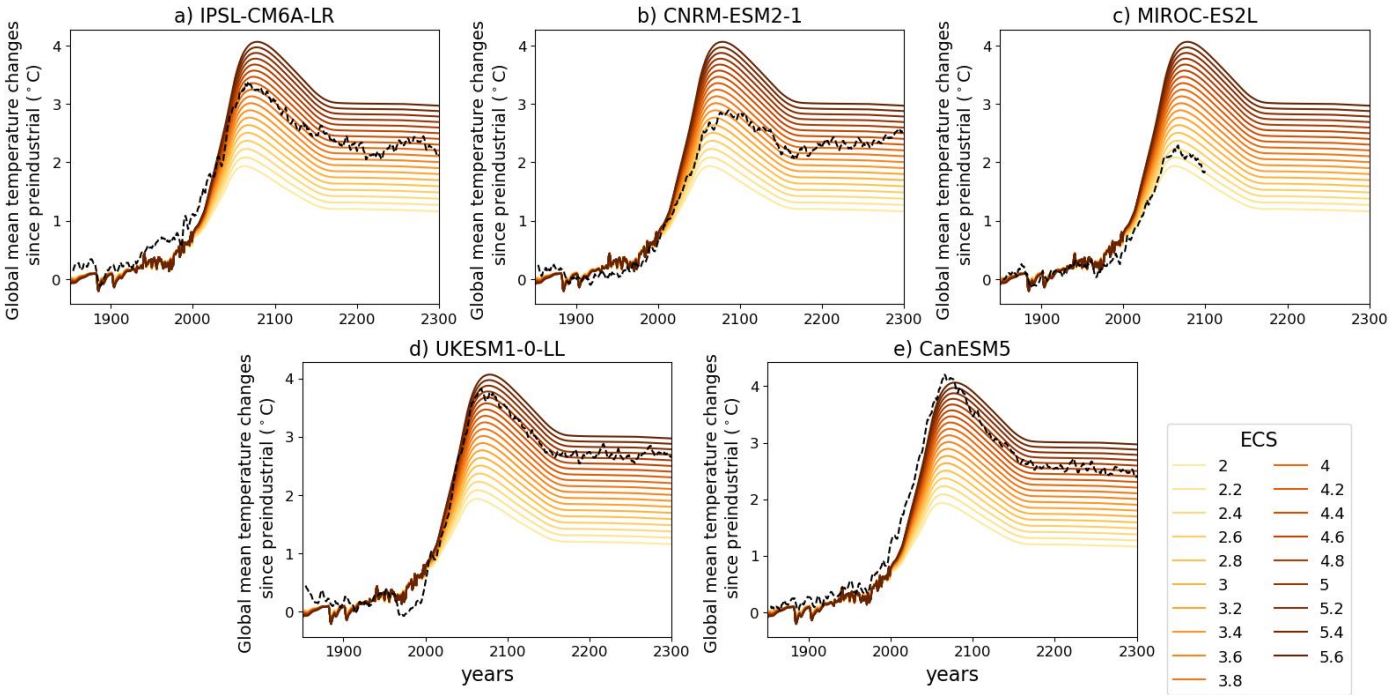

Figure S13 Results of the emulation process for the five ESMs considered. The figure compares the global mean temperature changes simulated by ESMs and ACC2 using different ECSs.

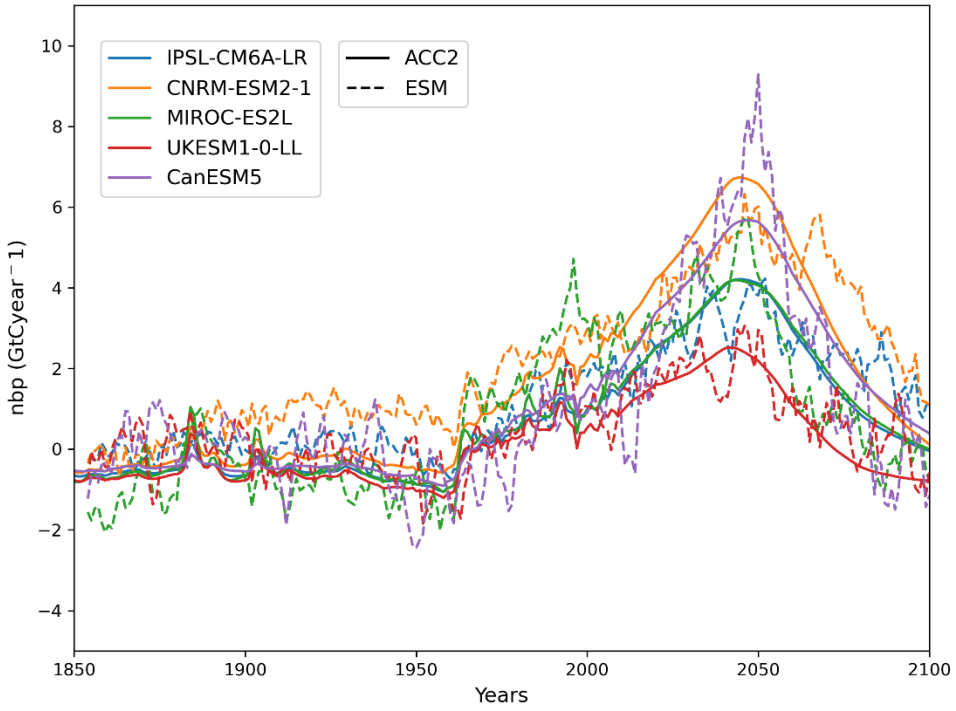

Figure S14 NBP projections of ACC2 emulated to each ESM. The BETA and Q10 values in ACC2 were adjusted to each ESM to best reproduce its NBP.

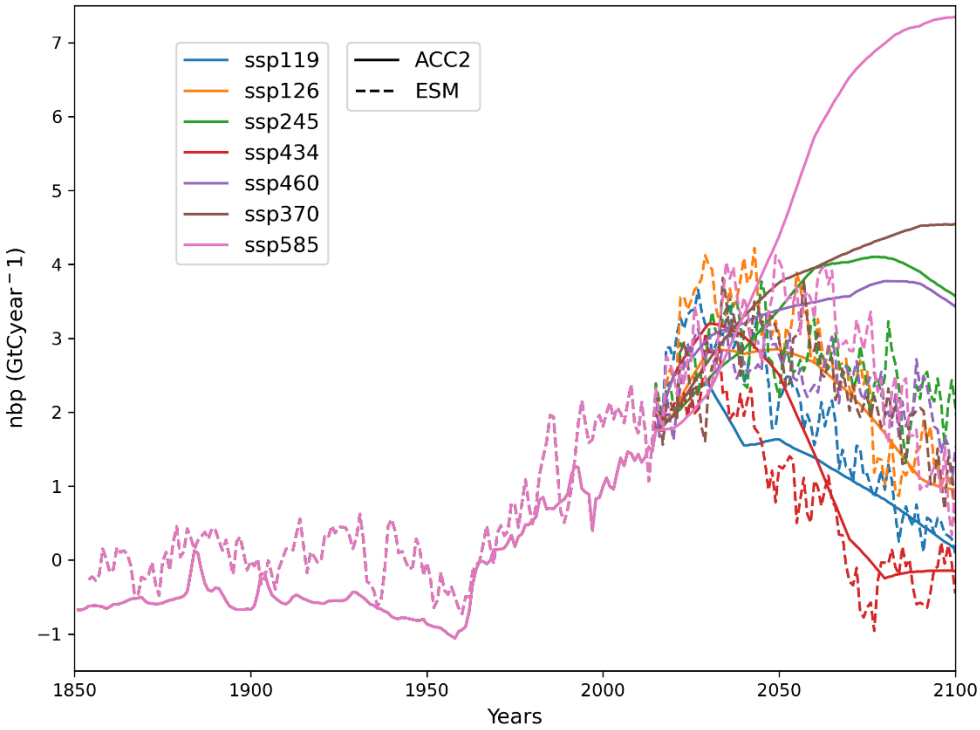

Figure S15 Results of the validation process for the emulation of IPSL-CM6A-LR for NBP. NBP values for seven SSP scenarios from ACC2 emulator are shown with respect to the CMIP6 simulation results of the considered model.

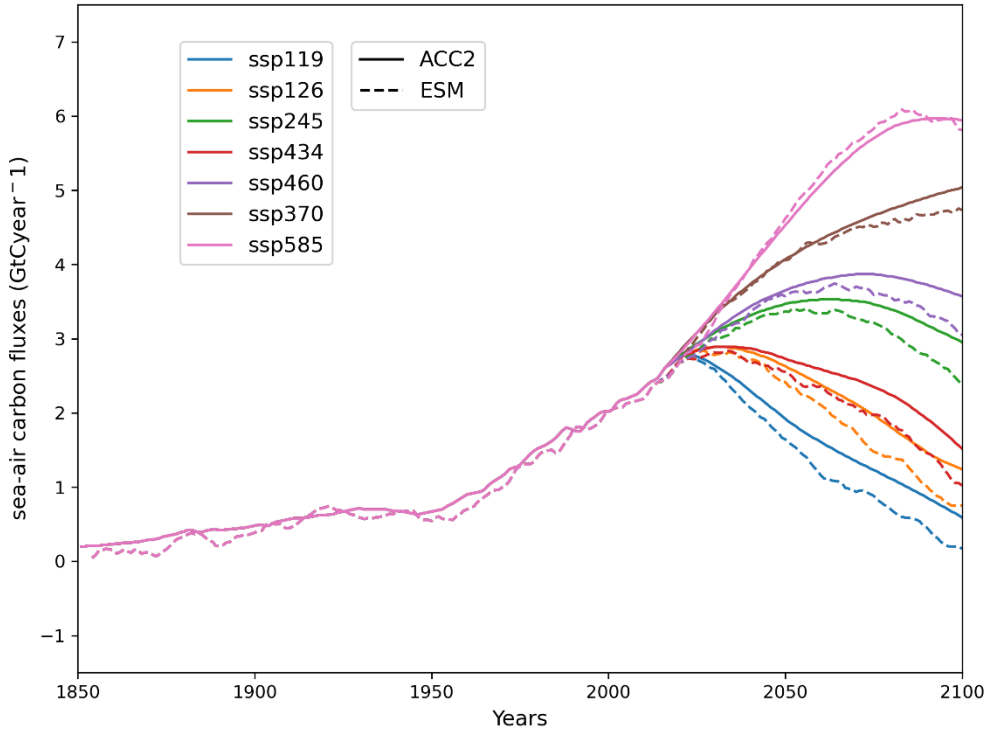

Figure S16 Results of the validation process for the emulation of IPSL-CM6A-LR for sea-air carbon fluxes. Sea-air carbon fluxes values for seven SSP scenarios from ACC2 emulator are shown with respect to the CMIP6 simulation results of the considered model.

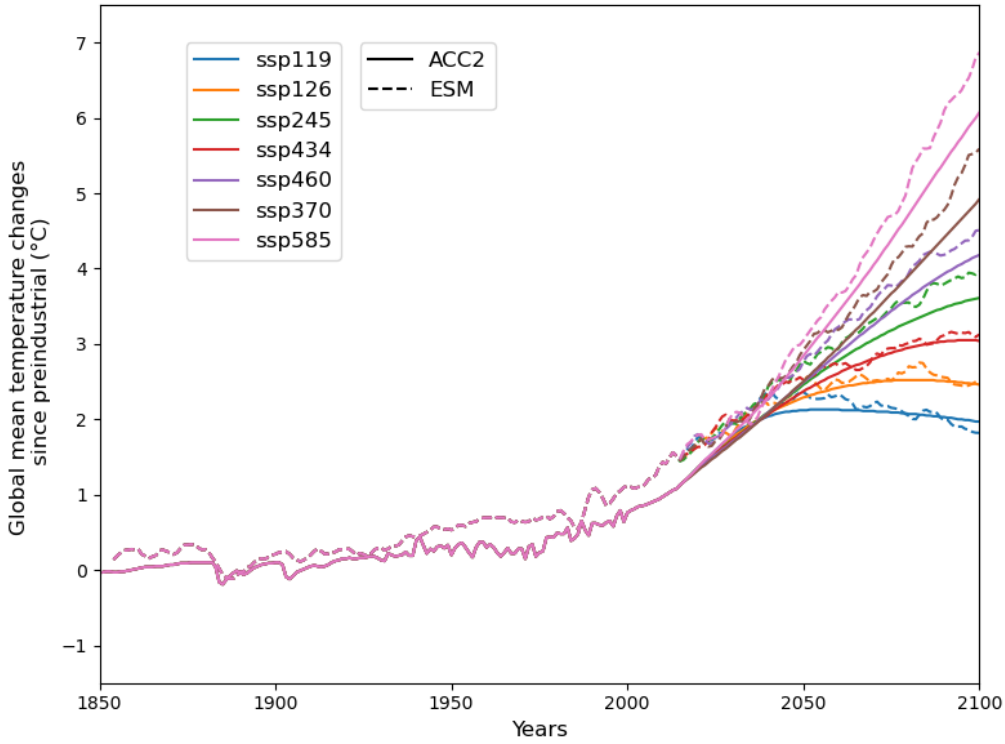

Figure S17 Results of the validation process for the emulation of IPSL-CM6A-LR for global mean temperature changes. Global mean temperature changes values for seven SSP scenarios from ACC2 emulator are shown with respect to the CMIP6 simulation results of the considered model.