Carbon cycle response to temperature overshoot beyond 2 $^{\circ}\mathrm{C}$ – an analysis of CMIP6 models

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Abstract

There is a substantial gap between the current emissions of greenhouse gases and levels required for achieving the 2 and 1.5 °C temperature targets of the Paris Agreement. Understanding the implications of a temperature overshoot is thus an increasingly relevant research topic. Here we explore the carbon cycle feedbacks over land and ocean in the SSP5-3.4-OS overshoot scenario by using an ensemble of Coupled Model Intercomparison Project 6 Earth system models. Models show that after the CO2 concentration and air temperature peaks, land and ocean are decreasing carbon sinks from the 2040s and become sources for a limited time in the 22nd century. The decrease in the carbon uptake precedes the CO2 concentration peak. The early peak of ocean uptake stems from its dependency on the atmospheric CO2 growth rate. The early peak of the land uptake occurs due to a larger increase in ecosystem respiration than the increase in gross primary production, as well as due to a concomitant increase in land-use change emissions primarily attributed to the wide implementation of biofuel croplands. The carbon cycle feedback parameters amplify after the CO2 concentration and temperature peaks due to inertia of the Earth system so that land and ocean absorb more carbon per unit change in the atmospheric CO2 change (stronger negative feedback) and lose more carbon per unit temperature change (stronger positive feedback) compared to if the feedback stayed unchanged. The increased negative CO2 feedback outperforms the increased positive climate feedback. This feature should be investigated under other scenarios.

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18 Key Points:

19	•	After a peak of CO_2 growth rate in the SSP5-3.4-OS scenario, land and ocean take up
20		carbon for at least 50 years but at a decreasing rate
21	•	The land sink decrease is due to the larger growth of respiration than photosynthetic
22		production and concurrent land-use change emissions
23	•	Under declining emissions, both land and ocean continue to take up carbon at an
24		asymmetrically larger rate

25 Abstract

There is a substantial gap between the current emissions of greenhouse gases and levels required 26 for achieving the 2 and 1.5 °C temperature targets of the Paris Agreement. Understanding the 27 implications of a temperature overshoot is thus an increasingly relevant research topic. Here we 28 explore the carbon cycle feedbacks over land and ocean in the SSP5-3.4-OS overshoot scenario 29 by using an ensemble of Coupled Model Intercomparison Project 6 Earth system models. Models 30 31 show that after the CO_2 concentration and air temperature peaks, land and ocean are decreasing carbon sinks from the 2040s and become sources for a limited time in the 22nd century. The 32 decrease in the carbon uptake precedes the CO_2 concentration peak. The early peak of ocean 33 34 uptake stems from its dependency on the atmospheric CO₂ growth rate. The early peak of the 35 land uptake occurs due to a larger increase in ecosystem respiration than the increase in gross primary production, as well as due to a concomitant increase in land-use change emissions 36 primarily attributed to the wide implementation of biofuel croplands. The carbon cycle feedback 37 38 parameters amplify after the CO_2 concentration and temperature peaks due to inertia of the Earth 39 system so that land and ocean absorb more carbon per unit change in the atmospheric CO_2 40 change (stronger negative feedback) and lose more carbon per unit temperature change (stronger positive feedback) compared to if the feedbacks stayed unchanged. The increased negative CO₂ 41 42 feedback outperforms the increased positive climate feedback. This feature should be 43 investigated under other scenarios.

44 Plain Language Summary

A large gap between required and currently planned greenhouse gas emission reductions makes
possible overshooting the 2 °C target of the Paris Agreement before the temperature can return
below the target levels. We explore the response of the global carbon cycle to overshoot by

analyzing the simulations of state-of-art models under an overshoot pathway, where the 48 emissions increase until the 2030s and exhibit a steep reduction thereafter. The land and ocean 49 continue to take up carbon from the atmosphere throughout the 21st century, albeit at a reduced 50 rate. The decrease in the ocean carbon uptake occurs before the CO₂ concentration peak due to 51 its dependence on the rate of the atmospheric CO_2 change, and the decrease in the land uptake 52 53 occurs due to a stronger increase in the ecosystem respiration than in the photosynthetic carbon absorption and simultaneous large land-use-change emissions from the expansion of biofuel 54 crops. After the peaks, land and ocean absorb more carbon from the atmosphere due to higher 55 CO₂ concentration and lose more carbon due to warmer temperatures. The influence of higher 56 CO₂ concentration wins over the influence of warming, allowing land and ocean to remain 57 carbon sinks till the end of the 21st century. 58

59 **1 Introduction**

The Paris Agreement aims for a long-term temperature target of holding global 60 temperature increase well below 2 °C and pursuing efforts to keep warming to no more than 61 62 1.5 °C (UNFCCC, 2015). However, there is a substantial gap between the required mitigation efforts to achieve this ambitious target and planned national policies towards emissions 63 reductions. According to the Intergovernmental Panel on Climate Change (IPCC) Special Report 64 "Global warming of 1.5 °C", achieving the temperature target without an overshoot, i.e., 65 temporarily exceeding the 1.5 or 2 °C limits, requires a rapid decline in global net anthropogenic 66 CO₂ emissions by 2030 up to at least 45% for the 1.5 °C and up to at least 25% for the 2.0 °C 67 targets. On the one hand, more than 100 countries have adopted or planned to adopt net-zero 68 targets by the year 2050, and China, which is currently the largest emitter of greenhouse gases 69 (GHGs), promised to become carbon neutral before 2060 (Mallapaty, 2020). On the other hand, 70

current nationally determined contributions indicate a slight increase in the CO₂ emissions in 2030 compared to 2020 levels meaning that current emission pledges may not be enough to achieve the Paris Agreement temperature targets (Höhne et al., 2020). Based on the assessment of current policies, Hausfather & Peters (2020) showed that global warming is on course to exceed 3 °C by the end of this century. Consequently, the possibility of temperature overshoot should be considered by the scientific community.

77 Our current understanding of the consequences of a temperature overshoot on the carbon cycle is limited. Several studies analyzed the carbon cycle feedbacks in the land and ocean under 78 overshoot scenarios (Boucher et al., 2012; Jones et al., 2016a; Zickfeld et al., 2016; Palter et al., 79 2018; Schwinger & Tjiputra, 2018; Tokarska et al., 2019; Jeltsch-Thömmes et al., 2020). Using 80 idealized ramp-up and ramp-down scenarios (with increasing and later decreasing CO2 81 concentration at a 1% year⁻¹ rate). Boucher et al. (2012) and Zickfield et al. (2016) showed that 82 land continues to act as a carbon sink for a long time after the temperature overshoots, while the 83 84 ocean turns into a source only a few decades after the ramp-down starts. Palter et al. (2018) considered an overshoot scenario, where CO₂ concentration increases until 2060, following a 85 86 Representative Concentration Pathway (RCP8.5), and rapidly decreases after. They showed that both land and ocean become a carbon source nearly two to three decades after the peaks of CO₂ 87 88 concentration and temperature. Schwinger & Tjiputra (2018) found that the ocean turns into a 89 carbon source only after a strong reduction in atmospheric CO₂ because the disequilibrium in the sea-air partial pressure is maintained for a long time after the peak of CO₂ concentration. The 90 91 bottom line is that existing studies all agree that land and ocean act as decreasing sinks at least for a couple of decades after the ramp-down starts, but it is difficult to assess the robustness of 92 the other findings of these studies. Indeed, the studies are based on different, highly idealized 93

scenarios. They also consider a limited number of models, and some of these models are of
intermediate complexity with little traceability to more complex models in the context of
overshoot scenarios. Thus, the role of more complex processes controlling the response of the
carbon cycle to the overshoot of the Paris Agreement temperature target remains largely
unexplored.

The response of the carbon cycle to the changes in the atmospheric CO_2 concentrations 99 100 and climate can be characterized by the carbon cycle feedback framework via carbon-101 concentration (β) and carbon-climate (γ) feedback parameters, respectively (Friedlingstein et al., 2006; Gregory et al., 2009; Jones et al., 2016b; Schwinger & Tjiputra, 2018; Williams et al., 102 103 2019; Arora et al., 2020; Jones & Friedlingstein, 2020). An application of these carbon cycle 104 feedback metrics to an overshoot scenario enables quantification of the contribution of carbonconcentration and carbon-climate feedback to the changes in carbon fluxes before and after the 105 peaks of CO₂ concentration and temperature. The framework has not been used for overshoot 106 107 scenarios with the exception of Schwinger & Tjiputra (2018) for the ocean. It is important to understand the carbon-concentration and carbon-climate feedbacks of both land and ocean under 108 109 overshoot scenarios through this feedback framework. The potential reversibility of feedbacks may influence mitigation pathways to achieve the Paris Agreement goals. 110

In this study, we take advantage of the newly available results from the state-of-art Earth system models (ESMs) developed under the Coupled Model Intercomparison Project 6, CMIP6 (Eyring et al., 2016) simulated under the shared socioeconomic pathway overshooting scenario named SSP5-3.4-OS (O'Neill et al., 2014). First, we evaluate carbon fluxes by ESMs against observational data sets. This step is required because inaccuracies in estimating past carbon uptakes by land and ocean may propagate to future predictions. Next, we investigate the

117	spatiotemporal changes in carbon fluxes by six CMIP6 ESMs. Because the SSP5-3.4-OS
118	includes the implementation of bioenergy crops in the future, we attempt to separate the net land
119	flux into land-use emissions from the expansion of bioenergy crops and sinks or sources in other
120	ecosystems. Finally, we apply the carbon cycle feedback framework to quantify the carbon cycle
121	feedbacks of the CMIP6 ESMs under the SSP5-3.4-OS pathway.
122	2 Description of the overshoot scenario and Earth system models
123	2.1 SSP5-3.4-OS
124	The SSP5-3.4-OS experiment is part of the Scenario Model Intercomparison Project,
125	ScenarioMIP (O'Neill et al., 2017; Tebaldi et al., 2020). It is designed to explore the
126	biogeophysical feedbacks of the Earth system to a strong ramp-down phase of CO ₂ concentration
127	and temperature after the historical and future steady increase until the mid-century
128	(Meinshausen et al., 2020). The GHG forcing of the SSP5-3.4-OS is based on the
129	implementation of SSP5 in the REMIND-MAgPIE model and its climate specifications are based
130	on emission-driven runs with MAGICC7.0. The SSP5-3.4-OS initially follows the high emission
131	(fossil-fuel development) SSP5-8.5 scenario and branches from it in 2040. Aggressive mitigation
132	thereafter causes a steep reduction in CO_2 emissions that become net zero by the 2080s, then go
133	net negative up to about -3.8 GtC year ⁻¹ by the year 2100, and ramp down to zero by the year
134	2170 (Figure S1). The total radiative forcing in SSP5-3.4-OS reaches 3.4 Wm ⁻² in 2100. The
135	carbon capture and storage (CCS) in this overshoot pathway reaches a cumulative amount of
136	almost 300 GtC (starting from the year 2011) by the end of the 21st century (Figure S1) and is
137	dominated by a second-generation bioenergy cropland expansion, mainly at the cost of pastures
138	(Hurtt et al., 2020).

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139	For the analysis, we use three adjoined experiments—historical from 1850 to 2014,
140	SSP5-8.5 for the period of 2015–2039, and SSP5-3.4-OS for the period of 2040–2100 (2300). In
141	addition to fully coupled simulations (COU), we use biogeochemically (BGC) coupled
142	simulations to study the carbon cycle feedbacks. The SSP5-3.4-OS-BGC is part of the Coupled
143	Climate–Carbon Cycle Model Intercomparison Project, C4MIP (Jones et al., 2016b). As the CO ₂
144	atmospheric concentration is not always reported in the model output, we use directly the
145	input4MIP data set which includes the atmospheric CO ₂ concentration pathway used in the
146	concentration-driven simulations (Meinshausen et al., 2016; 2020).
147	2.2 Earth system models
148	To date, six CMIP6 ESMs have provided carbon cycle outputs for the SSP5-3.4-OS
149	pathway (Table 1). The models are described in detail elsewhere (Arora et al., 2020; Séférian et
150	al., 2020). Four ESMs (apart from MIROC-ES2L and CESM2-WACCM) provide extended
151	outputs up to the end of the 23 rd century. Five ESMs (apart from CESM2-WACCM) provide
152	outputs for both COU and BGC simulations till the end of the 21st century, and the IPSL-CM6A-
153	LR – till the 23 rd century. The presence of both COU and BGC simulation outputs enables
154	investigating the carbon cycle feedbacks parameters under the SSP5-3.4-OS scenario. The six
155	models differ in terms of the structure and the representation of carbon cycle processes. Among
156	them, three models represent explicitly the nitrogen cycle over land, two include a fire
157	component, one has dynamic vegetation, and one accounts for permafrost (Table 1). All models
158	simulate inorganic carbon in the ocean, and among them, two models also consider dissolved
159	organic carbon.

For the estimates of the land-use change (LUC) emissions, we use a variable *fLUC* that is present in four models (absent in CanESM5 and MIROC-ES2L). For the analysis, we use the 162 carbon fluxes anomalies relative to the branching year values for changes in carbon pools and long-term mean preindustrial control (piControl) values for changes in carbon fluxes. For both 163 pools and fluxes, we subtract the long-term piControl linear trend to remove any residual trend 164 (Figure S2). In the case of fluxes, we subtract long-term piControl mean values and not the 165 values of branching years to avoid creating a drift caused by the interannual variability. Only one 166 ensemble member was available for all the experiments required. Therefore, for the analysis, we 167 use only one ensemble member of each model documented in Table S1.

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169 Table 1. Major characteristics of the Earth system models, and their simulation setup considered in our study	
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ESM	IPSL-CM6A-LR	CNRM-ESM2-1	CanESM5	UKESM1-0-LL	MIROC-ES2L	CESM2-WACCM
Center (country)	IPSL (France)	CNRM-CERFACS (France)	CCCma (Canada)	MOHC (UK)	JAMSTEC/NIES/AORI (Japan)	NCAR (USA)
Reference	(Boucher et al., 2020)	(Séférian et al., 2019)	(Swart et al., 2019a)	(Sellar et al., 2019)	(Hajima et al., 2020)	(Danabasoglu et al., 2020)
SSP5-3.4-OS period	2040-2300	2015-2100	2040-2300	2040-2100	2015-2100	2040-2299
Land carbon	ORCHIDEE, br.2.0	ISBA-CTRIP	CLASS-CTEM	JULES-ES-1.0	VISIT-e	CLM5
Nitrogen cycle	No	Implicit	No	Yes	Yes	Yes
Permafrost	No	No	No	No	No	Yes
Fires	No	Yes (natural)	No	No	No	Yes
Dynamic vegetation	No	No	dynamic wetlands	Yes	No	No
PFT	15	16	4 (CLASS), 9 (STEM)	9 natural and 4 crop/pasture	13	22
LUC	Yes	Yes	Yes	Yes	Yes	Yes
Ocean carbon	PISCES-v2	PISCESv2-gas	СМОС	MEDUSA-2.1	OECO2	MARBL-BEC
Representation of marine sediments*	Meta-model	Meta-model	No	Sediment Box	Meta-model	No
SSP-5-3.4-OS-BGC	Yes (extended till 2300)	Yes	Yes	Yes	Yes	No
esm-SSP5-3.4-OS**	No	No	No	Yes	Yes	No
Data set DOIs***	https://doi.org/10.22 033/ESGF/CMIP6.5 251	https://doi.org/10.22 033/ESGF/CMIP6.4 165	https://doi.org/10.2 2033/ESGF/CMIP 6.3673	https://doi.org/10.2 2033/ESGF/CMIP6 .6298	https://doi.org/10.22033 /ESGF/CMIP6.5710 https://doi.org/10.22033	https://doi.org/10.22 033/ESGF/CMIP6. 10094
	https://doi.org/10.22 033/ESGF/CMIP6.5 195	https://doi.org/10.22 033/ESGF/CMIP6.4 068	https://doi.org/10.2 2033/ESGF/CMIP 6.3610	https://doi.org/10.2 2033/ESGF/CMIP6 .6113	/ESGF/CMIP6.5602	https://doi.org/10.22 033/ESGF/CMIP6. 10071

https://doi.org/10.22 033/ESGF/CMIP6.5 271	https://doi.org/10.22 033/ESGF/CMIP6.4 221	https://doi.org/10.2 2033/ESGF/CMIP 6.3696	https://doi.org/10.2 2033/ESGF/CMIP6 .6405	https://doi.org/10.22033 /ESGF/CMIP6.5767 https://doi.org/10.22033	https://doi.org/10.22 033/ESGF/CMIP6. 10115
https://doi.org/10.22	https://doi.org/10.22	https://doi.org/10.2	https://doi.org/10.2	/ESGF/CMIP6.5582	https://doi.org/10.22
033/ESGF/CMIP6.5 269	033/ESGF/CMIP6.4 047	2033/ESGF/CMIP 6.3694	2033/ESGF/CMIP6 .6397	https://doi.org/10.22033 /ESGF/CMIP6.5769	033/ESGF/CMIP6. 10114
	https://doi.org/10.22 033/ESGF/CMIP6.4 223	https://doi.org/10.2 2033/ESCE/CMIP	https://doi.org/10.2 2033/ESGF/CMIP6 .6055	https://doi.org/10.22033 /ESGF/CMIP6.5512	
	223	6.3600	https://doi.org/10.2	https://doi.org/10.22033 /ESGF/CMIP6.5496	
		https://doi.org/10.2 2033/ESGF/CMIP	.6409	https://doi.org/10.22033	
		6.3697	https://doi.org/10.2 2033/ESGF/CMIP6	/ESGF/CMIP6.5525	
		https://doi.org/10.2 2033/ESGE/CMIP	.6401		
		6.3695	https://doi.org/10.2 2033/ESGF/CMIP6 .5953		
			https://doi.org/10.2 2033/ESGF/CMIP6 .5929		
			https://doi.org/10.2 2033/ESGF/CMIP6 .5969		
			https://doi.org/10.2 2033/ESGF/CMIP6 .12203		

170 * from Séférian et al. (2020)

171 ** esm-SSP5-3.4-OS refers to emission-driven simulation, as opposed to concentration-driven SSP5-3.4-OS and SSP-5-3.4-OS – BGC simulations.

172 **3 Evaluation of Earth system models**

173	The historical carbon uptake by land and ocean is relatively well constrained, and the
174	land uptake should be nearly zero when cumulated over the last 200 years (Gruber et al., 2019;
175	Khatiwala et al., 2009). Thus, ESMs that simulate too large a land uptake in the historical period
176	should be treated carefully for future predictions. In this section, we evaluate the ensemble of
177	ESMs that we use in a consistent way against corresponding observational data for
178	understanding inter-model discrepancies.
179	3.1 Data and methods
180	We evaluate the land and ocean carbon fluxes using three different approaches. First, we
181	compare the decadal means, interannual variability (IAV), and linear trends in global land and
182	ocean anthropogenic carbon uptakes by ESMs with Global Carbon Budget 2019, GCB2019 v.1.0
183	(Friedlingstein et al., 2019) in 1985–2018. Here we adopt the GCB2019 net land flux computed
184	as a residual between fossil fuel emissions, atmospheric growth, and the ocean uptake rather than
185	the more uncertain land uptake directly estimated by biogeochemical process models. For
186	evaluation of the ocean uptake, we use both values averaged from models and data-driven
187	products.
188	Second, we evaluate carbon fluxes in nine regions, covering nearly the entire globe, in six
189	ESMs against the estimates, based on the observations of the REgional Carbon Cycle
190	Assessment and Processes (RECCAP) project further harmonized and completed by additional

data and synthesized for 9 land regions covering nearly the entire globe (Ciais et al., 2020), the

192 most comprehensive global bottom-up carbon flux synthesis to date.

193	The land carbon uptake estimated by Ciais et al. (2020) includes both anthropogenic and
194	natural sinks, unlike GCB2019 that includes only the anthropogenic uptake. For evaluation
195	against both approaches, the NBP anomalies from piControl are used. This causes some level of
196	uncertainty in comparing the land carbon uptake in the nine RECCAP regions and requires
197	careful interpretation.
198	Finally, the two inversion-based data sets, CarbonTracker 2019 (CT2019) by Jacobson et
199	al. (2020) and Copernicus Atmospheric Monitoring Service (CAMS) by Chevallier (2013) are
200	used to evaluate the spatial variation of the land and ocean carbon uptake in 2000–2014.
201	3.2 Results of the evaluation
202	Figure 1 shows the evaluation results of the land and ocean carbon fluxes by ESMs
203	against existing data sets. Note that the observational products of the ocean were corrected to
204	deduce the anthropogenic ocean CO_2 uptake, by removing from their total CO_2 flux estimate a
205	pre-industrial steady-state natural ocean CO2 outgassing (of about 0.78 GtC year-1 from
206	GCB2019). This allows a comparison with the ESMs estimates of anthropogenic ocean uptake
207	relative to their respective piControl (Friedlingstein et al., 2019). The ESMs we considered
208	estimate a higher decadal mean of net land carbon uptake than GCB2019 and slightly
209	underestimate the global mean and IAV of ocean carbon uptake relative to data-driven products
210	(Figure 1a). Among six ESMs, CNRM-ESM2-1 estimates the highest cumulative land carbon
211	uptake and the least cumulative ocean carbon uptake for the 1850-2014 period (Figure S3).
212	The ESMs agree with the inversions on the ocean acting as a carbon sink globally.
213	Discrepancies are in the tropical areas of the eastern equatorial Pacific Ocean, the northern
214	Indian Ocean, and along the Californian Current. CNRM-ESM2-1 estimates a lower carbon

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215	uptake in the North Atlantic Ocean, and MIROC-ES2L estimates weaker outgassing in the
216	equatorial Pacific Ocean than inversions (Figure 1b). These discrepancies were reported by
217	earlier publications (Hajima et al., 2020; Séférian et al., 2019).
218	The inter-model spread for the net land carbon uptake is much larger than for the ocean
219	sink. GCB2019 reports a smaller net land carbon sink (including LUC emissions) on average
220	during 1985–2018 than ESMs (Figure 1a). The higher land sink by CNRM-ESM2-1 and
221	MIROC-ES2L in the historical period than GCB2019 and other ESMs corresponds to a larger
222	increase in the land carbon pools (Figure S3). IPSL-CM6A-LR is the closest to GCB2019 in
223	terms of the IAV of the land sink (defined via standard deviation) among the ESMs. MIROC-
224	ES2L and UKESM1-0-LL estimate higher IAV, and CNRM-ESM2-1 and CESM2-WACCM
225	underestimate lower IAV than GCB2019. The spatial variations of the net land carbon uptake by
226	the two atmospheric inversions agree in sign but disagree in magnitude with each other, even at
227	the scale of coarse latitude bands (Friedlingstein et al., 2019 and Figure 1b). The inversions
228	estimate a higher land sink in the north than ESMs and a carbon source in the tropics that is not
229	present in the ESMs. MIROC-ES2L estimates a slightly higher net biome production (NBP) sink
230	in Northern Hemisphere than other models (that is still lower than in the inversions). UKESM1-
231	0-LL estimates slightly high carbon uptake in tropical Amazonia and Africa, which Sellar et al.
232	(2019) attributed to a small overestimation of tree fraction in savanna biomes compared to
233	observational data sets.



Figure 1. An evaluation of Earth system models (ESMs) against observational and inversion datasets. The sign convention is that sources of CO₂ to the atmosphere are negative values and removals/sinks are positive. Panel (a) shows the interannual variability of land (net biome

production, NBP) and ocean (fgco2) carbon uptakes by ESMs and Global Carbon Budget 238 (GCB2019) and three data-driven products (Denvil-Sommer et al., 2019; Landschützer et al., 239 2016; Rödenbeck et al., 2014). Data-driven products are corrected for pre-industrial outgassing 240 of 0.78 GtC year⁻¹. Shaded area indicates uncertainty provided by Friedlingstein et al. (2019). 241 The residual NBP values for GCB2019 in the table are calculated using the GCB2019 ocean 242 243 uptake that is the average of several global ocean biogeochemistry models that reproduce the observed mean ocean sink of the 1990s and are compared to the NBP anomaly from piControl by 244 ESMs. Panel (b) shows the 2000–2014 mean annual carbon uptake by land and ocean estimated 245 by ESMs and two atmospheric inversions CT2019 and CAMS. Panel (c) shows NBP for nine 246 RECCAP regions in 2000–2009 according to Ciais et al. (2020). Error bars indicate estimates of 247 uncertainty from Ciais et al. (2020). 248

All ESMs estimate lower land carbon uptake in Russia, South Asia, and Southeast Asia 249 than the corresponding inventory-based estimates in RECCAP (Figure 1c). To understand the 250 251 reasons for this underestimation, we compared other land fluxes by ESMs with those given by Ciais et al. (2020) (Figure S4). ESMs adequately estimate net primary production (NPP) relative 252 253 to RECCAP. CESM2-WACCM and IPSL-CM6A-LR reproduce heterotrophic respiration (R_H) well. However, most models estimate higher than RECCAP estimates R_H in North America, East 254 255 Asia, South-East Asia, and Australia, possibly because they do not include harvest processes that decouple NPP from $R_{\rm H}$. The *fLUC* emissions are underestimated by ESMs in tropical regions. 256 This likely reflects the fact that *fLUC* diagnosed by ESMs follows a definition that does not 257 258 cover all LUC emission terms of the models' realm (e.g., legacy soil carbon emissions after LUC, biomass decay after LUC are not in *fLUC*). There is also the fact that models do not 259 reproduce some LUC emission processes such as shifting cultivation or degradation that were 260

included in the LUC emissions from RECCAP. The difference between NPP and R_H is higher in
RECCAP estimates than in ESMs in all regions. Thus, these component fluxes cannot explain
the discrepancies between ESM and RECCAP estimates, suggesting there could still be missing
processes in these state-of-the-art models (Ciais et al., 2020).

The CMIP6 ESMs show higher historical land carbon uptake than GCB2019 and lower uptake than estimates by Ciais et al. (2020). This is probably due to the differences in terms included in the land sink by two evaluation approaches – anthropogenic sink in GCB2019 and anthropogenic and natural sinks in the study by Ciais et al. (2020). However, the use of both NBP anomaly from piControl (Figure 3c) and NBP absolute value (Figure S4d) lead to very similar results. Whether the natural or anthropogenic terms of land uptake in certain regions were underestimated requires further analysis and more attention in future studies.

4 Analysis of the carbon cycle feedbacks under the SSP5-3.4-OS pathway

4.1 Temporal variation of global carbon fluxes under SSP5-3.4-OS

In the concentration-driven SSP5-3.4-OS scenario, the CO₂ concentration as given by input4MIPs peaks in the year 2062 at 576.2 ppm (Figure 2). According to the scenario design, strong mitigation policies to reduce GHGs emissions, which include bioenergy crops and CCS (BECCS), start in 2040 and result in an immediate decrease in the CO₂ growth rate that peaks in 2041 (O'Neill et al., 2017; Meinshausen et al., 2020). Both peaks of the CO₂ concentration and CO₂ growth rate have important implications on the carbon fluxes discussed hereafter. The six ESMs demonstrate large differences in the response of global mean surface air

temperature (GSAT) to the prescribed changes in CO₂ concentration under the SSP5-3.4-OS.

282 The magnitudes of the overshoot vary from 2.4 °C in MIROC-ES2L to 4.1 °C in CanESM5, the

timings of the GSAT peaks vary from the late 2040s in MIROC-ES2L to the late 2070s in 283 CNRM-ESM2-1, and the rates of the GSAT ramp-down vary from a steep decrease in CanESM5 284 to almost no decrease in CNRM-ESM2-1. The multi-model mean GSAT is 2.32 ± 0.28 °C at the 285 end of the 23rd century. Its temporal trajectory differs among ESMs from a weak persistent 286 decrease in CanESM5 and IPSL-CM6A-LR to an increase in CESM2-WACCM and CNRM-287 ESM2-1. In all six ESMs, the growth rate of GSAT peaks in the early 2040s, just a few years 288 after the peak of the CO₂ growth rate (Figure S5a).

289

A previous idealized scenario-based study reported that the transient climate response to 290 cumulative carbon emissions (TCRE) is larger in the ramp-down period than in the ramp-up 291 292 period of carbon emissions (Zickfeld et al., 2016). Our analysis could not confirm this, as the majority of ESMs showed a decrease in TCRE during the ramp-down period (Figure S5b). The 293 inter-model differences in TCRE may be related to the model parametrization, and particularly 294 the effective equilibrium climate sensitivity (ECS) as pointed out by Tachiiri (2020). However, 295 296 further investigation is necessary for a deeper understanding of the underlying reasons for the inconsistency between 1%-increase idealized and more societally relevant SSP5-3.4-OS. 297

The land and ocean carbon uptakes always decrease after the peak of the CO₂ growth rate 298 (and before the peak of CO_2 concentration). However, these two reservoirs continue to remove 299 CO₂ from the atmosphere at least for 50 years (Figures 2b and 2c). ESMs with COU simulation 300 extended outputs till the 22nd and 23rd centuries show that the land and ocean turn into a carbon 301 source for a limited time in the 22nd century. At the end of the 22nd century, the land becomes 302 nearly net-zero and the ocean remains a weak carbon sink. Among ESMs, CESM2-WACCM 303 -that accounts for permafrost processes- has the lowest value of land carbon uptake (zero to 304 weak source) at the end of the 23rd century. It simulates a continued carbon source from high 305

latitude carbon soils till the end of the study period that is almost entirely compensated by the 306 vegetation greening (Figure S6). By the end of the 23rd century, the accumulated carbon is stored 307 mainly in the Southern Ocean and over mid-to-high latitudes of the Northern Hemisphere in the 308 land. When looking at the changes in the carbon reservoirs (Figure S3), the ESMs agree that 309 during the ramp-down, the ocean releases some previously-stored carbon to the atmosphere for a 310 311 limited period (of around 50 years) and continues to take up carbon at a decreased rate thereafter. The long-term response of land to the overshoot largely differs among ESMs to the extent from 312 returning to the preindustrial levels of carbon storage in CanESM5 to the increase in land carbon 313 pool half the size of the cumulative ocean flux in IPSL-CM6A-LR and twice the size of the 314 cumulative ocean flux in CNRM-ESM2-1. 315

The estimated behavior of land and ocean under overshoot is consistent with existing 316 studies. Jones et al. (2016a) used four ESMs and RCP2.6 scenario, which has an earlier peak of 317 CO_2 growth rate (and CO_2 concentration) and a slower ramp-down phase than this study. They 318 reported that land and ocean remain carbon sinks for more than 100 years after the peak of the 319 CO₂ growth rate. Palter et al. (2018) used one ESM and RCP8.5-based overshoot scenario, which 320 has a later peak of CO₂ growth rate (and CO₂ concentration) and a more rapid ramp-down phase 321 than this study. They reported that land and ocean turn to carbon sources in less than three 322 323 decades after the peak of CO_2 concentration. Based on the three studies, earlier CO_2 peak and slower ramp-down cause the land and ocean to act as carbon sinks for a longer time. 324



Figure 2. Time series and peak years of the global annual total or mean variables of ESMs, including (a) GSAT, and CO₂ concentration, (b) ocean uptake, (c) NBP, (d) GPP, (e) TER, and (f) LUC emissions. Air temperature anomaly is taken from 1850–1899 mean; other variables are anomalies from piControl simulation. The ensemble mean (dashed brown line) of six ESMs is calculated till the year 2100 with a shaded area indicating ensemble spread via standard deviation. The CO₂ concentration and its growth rate are shown with dashed black and blue curves on panels (a) and (b). The years of peak atmospheric CO₂ concentration and CO₂ growth

rate are indicated by vertical black and blue dashed lines, respectively. Panel (g) indicates the
years of peak of the variables.

4.2 The peaks of land and ocean carbon uptakes

The peaks of carbon uptake by land and ocean occur before the peaks of CO₂ concentration, temperature, gross primary production (GPP), terrestrial ecosystem respiration (TER), and its components autotrophic (R_A) and heterotrophic (R_H) respirations (of which R_H peaks the latest). To identify the reasons for those varying peak times, it is essential to look at the

341 derivatives of the variables (Figures S7).

The response of air temperature lags CO₂ concentration, owing to the inertia of the 342 climate system at the time the CO₂ starts to decrease. McKinley et al. (2020) and Schwinger and 343 Tjiputra (2018) pointed out that the CO₂ growth rate dominates the variability in the global ocean 344 on year-to-year timescales, hypothesizing that other internal and external drivers may become 345 more important in the altered state of the ocean in the future. Using the outputs of six CMIP6 346 ESMs, we show that global ocean carbon uptake is nearly a linear function of the atmospheric 347 CO₂ growth rate, confirming the finding discussed above. The slope of the function changes after 348 the peak of the CO₂ growth rate from 0.74 ± 0.03 to 0.26 ± 0.02 GtC year⁻² (average and 349 standard deviation of six ESMs), with a clear hysteresis behavior (Figure 3b). At the peak of the 350 CO₂ growth rate, the linear function curls up with the negative CO₂ growth values. The extended 351 352 simulation outputs available for four models indicate that the trajectory of the ocean uptake curve



is directed towards zero, closing the cycle after a limited period of carbon source.

Figure 3. The dependency of (a) land and (b) ocean carbon uptake on the atmospheric CO₂ growth rate by CMIP6 Earth system models under historical and SSP-5-3.4-OS pathway. The markers "+" indicate the historical period (1850–2014), markers "*" and "×" indicate the periods before and after the peak of CO₂ growth rate in 2041, respectively. In the case of the land uptake, the points correspond to decadal moving averages, annual points are shown in pale colors.

The ESMs reveal a weaker linear dependency of the land carbon uptake on the CO₂ 360 growth rate than on the ocean uptake (Figure 3a). It is well-known that the two largest land 361 carbon fluxes, namely GPP and TER, primarily depend on the CO₂ concentration, temperature, 362 and soil moisture, as well as other factors not modeled by ESM such as land management 363 intensity, and nutrient limitations (Ciais et al., 2020; Huntzinger et al., 2017). In addition, land 364 carbon uptake experiences much larger interannual variability. When the interannual variability 365 is removed, the linear dependency of the land uptake on the CO_2 growth rate becomes nearly 366 parallel to that of ocean uptake. 367

The nearly linear dependency of the land and ocean carbon uptakes on CO_2 growth rate characterizes the system response to the forcing rate of change (CO_2 growth rate), i.e., the level

of departure from the existing equilibrium state. The hysteresis behavior during the ramp-down 370 period indicates how the system responds to the forcing magnitude (CO₂ concentration). Figures 371 372 2 and 3 suggest that on short time-scales, the changes in the land and ocean carbon uptakes are strongly related to the state disequilibrium. The greater the disequilibrium is, (i.e., the larger the 373 CO_2 growth rate is), the larger the responses of the land and ocean carbon uptakes are. In the 374 375 longer time scales, e.g., timescales longer than carbon residence time in the pool, the changes in the land and ocean carbon uptakes may be strongly related to the state of the system itself. 376 Previously, Koven et al. (2015) showed an apparent reduction in the soil carbon residence time 377 when the forcing rate is too fast because carbon only goes through the fast pools and returns to 378 the atmosphere. We showed that this may be true for land and ocean carbon pools. Future studies 379 should further investigate this feature. 380

381 4.3 Impact of land-use change emissions

The changes in the growth rate of GPP and TER alone cannot explain the early land 382 carbon uptake peak in some models, e.g., IPSL-CM6A-LR. The BECCS-related anthropogenic 383 384 LUC emissions in the 2040s may also contribute to the early peak of the land carbon uptake although models do not represent explicitly the higher yield or specific biophysical parameters of 385 bioenergy crops (to our knowledge). In the SSP5-3.4-OS, the only type of anthropogenic carbon 386 emissions that increases after the 2040s is that of agriculture, forestry, and other land use 387 (AFOLU, Figure S8). We postulate that both the larger growth rate of TER than GPP and 388 increased LUC emissions cause the early peak of land uptake. The expansion of biofuel crops 389 may cause a weakening of the land sink capacity because these systems dedicated to biomass 390 production for harvest no longer have the potential for storing carbon e.g., in soils or biomass. 391

392	The spatiotemporal variation of the bioenergy cropland area under the SSP5-3.4-OS is
393	formulated in the Harmonization of Global Land-Use Change and Management (LUH2) data set
394	(Hurtt et al., 2020). In most ESMs, the areas where the bioenergy crops are implemented
395	correspond to areas of decreases in the land carbon uptake after the CO ₂ growth rate peaks
396	compared to the prior period, e.g., eastern South America, Europe, the eastern coast of North
397	America, and the northern part of Southeast Asia (Figures S7b, S9, and S10). A strong impact of
398	LUC on the carbon uptake is remarkable for the IPSL-CM6A-LR and UKESM1-0-LL. Yet, the
399	effect of LUC on newly converted bioenergy croplands vs. those of climate change on remaining
400	natural ecosystems cannot be separated in each ESM grid cell, from the available simulations.
401	The modeling groups use varying definitions of the land-use change due to different system
402	boundaries and different definitions of the human perturbation of ecosystems resulting in
403	inconsistent reporting of LUC emissions estimates among the ESMs (Gasser & Ciais, 2013).
404	This uncertainty should be addressed in related future intercomparison projects.

405 **5** Quantifying the Carbon cycle feedbacks under the SSP5-3.4-OS pathway

406 5.1 Definitions and method

We apply the carbon cycle feedback framework on the five ESMs (apart from CESM2-WACCM) that have all the necessary data for calculations explained below. The carbonconcentration feedback parameter (β , GtC ppm⁻¹) indicates the changes in the carbon storages of land and ocean in response to changes in the atmospheric CO₂ concentration. The carbon-climate feedback parameter (γ , GtC °C⁻¹) indicates the changes in the carbon storage in response to the changes in GSAT. The change in the carbon storages of land and ocean can then be decomposed into the β and γ contributions ($\beta \times \Delta CO_2$ and $\gamma \times \Delta T$, respectively), and a residual term ϵ :

$$\Delta C = \beta \times \Delta CO_2 + \gamma \times \Delta T + \varepsilon \tag{1}$$

414	The β contribution (or β uptake) is the changes in carbon storage (GtC) or flux (GtC year-
415	¹) credited to the carbon-concentration feedback and γ contribution is the changes in carbon
416	storage or flux credited to the carbon-climate feedback. ΔC is the difference in the carbon storage
417	relative to the piControl simulation, ΔCO_2 is the difference in the global atmospheric CO_2
418	concentration relative to the value of the year 1850 as given by input4MIP (284.32 ppm), and ΔT
419	is the difference in temperature simulated by each ESM relative to 1850–1899 mean GSAT. In
420	the case of the SSP5-3.4-OS, neither ΔCO_2 nor ΔT become negative any time after the peaks.
421	The carbon cycle feedback parameters can be diagnosed from the differences in COU,
422	BGC, and radiatively coupled (RAD) simulations of ESMs. In the BGC simulation, only changes
423	in the CO ₂ concentration, and not temperature, affect the land and ocean carbon-cycle processes.
424	In the RAD simulation, in contrast, changes in the CO ₂ concentration affect the radiation balance
425	of the atmosphere but are not seen by the carbon cycle. There are two commonly used
426	approaches to estimate the carbon cycle feedback parameters, (1) β from BGC, γ from RAD, and
427	(2) β from BGC, γ from the difference between COU and BGC (thereafter, COU–BGC). In this
428	study, we used the latter approach because no RAD simulations are currently available for SSP5-
429	3.4-OS. In this case, the residual term ε of Equation (1) is integrated into γ . Previous studies
430	show that the absolute values of γ estimated by the COU–BGC approach can appear 2–3 times
431	larger than the RAD approach because RAD simulation does not include the suppression of
432	carbon transport to the deep ocean due to weakening ocean circulation (Schwinger & Tjiputra,
433	2018; Arora et al., 2020).

434 We estimate β and γ for land (β_{land} and γ_{land}) and ocean (β_{ocean} and γ_{ocean}) using the land 435 carbon pool (*cLand*) and cumulative ocean carbon flux (*fgco2*) because not all models provide

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436	the ocean carbon pools (<i>dissic</i> and <i>dissoc</i>). Before calculations, we confirmed that β and γ
437	estimated using the carbon pool variables agree with corresponding estimates obtained from the
438	cumulative carbon fluxes, i.e., NBP and cLand over land and fgco2 and dissic+dissoc over the
439	ocean (not shown). Furthermore, we decomposed the land β in terms of underlying processes,
440	such as GPP, R_A , and R_H , using cumulative fluxes over time.
441	5.2 Carbon cycle feedbacks before mitigation activities
442	The β and γ feedback parameters depend on the state of the system and scenario
443	(Friedlingstein et al.; 2006, Jones et al., 2016b; Willeit et al., 2014). To understand the carbon
444	cycle feedbacks under the SSP5-3.4-OS overshoot pathway, it is essential to first investigate the
445	changes in the carbon pools (that define the state of the system) over the historical period. ΔC of
446	the five ESMs varies in the historical period to the extent that ΔC_{land} is either positive, e.g., in
447	CNRM-ESM2-1, IPSL-CM6A-LR, and UKESM1-0-LL, or negative, e.g., in CanESM5 and
448	MIROC-ES2L (Figure S3), resulting in positive and negative β (Figures 4 and 5) at the
449	beginning of the 21^{st} century. The negative β in some models is likely a result of decreases in the
450	carbon storage due to LUC emissions.
451	Before the peak of CO ₂ concentration, β_{ocean} decreases (becomes less positive) in all five

ESMs (Figure 4a) because increasing anthropogenic carbon emissions exceed the ability of the ocean to absorb carbon (Friedlingstein et al., 2006; Gregory et al., 2009). In all models apart from CNRM-ESM2-1, β_{land} increases at the beginning of the 21st century and continues to increase after the CO₂ concentration peak at a rising rate. CNRM-ESM2-1 exhibits larger uptake during the historical period before the year 2000 that, perhaps, causes high ΔC already at the beginning of the 21st century, leading to overly high β_{land} . Besides, unlike other models, CNRM-ESM2-1 shows decreasing positive γ_{ocean} throughout the study period.



Figure 4. Carbon-concentration β (GtC ppm⁻¹) on the left and carbon-temperature γ (GtC °C⁻¹) feedback parameters for (a) ocean estimated from cumulative flux fgco2, and (b) land estimated

462	from cumulative NBP. Estimated feedback parameters for cumulative land fluxes: (c) GPP, (d)
463	$R_{A_{i}}$ and (e) R_{H} . The figures in the first column show β as a function of time (year) and in the
464	second column as a function of ΔCO_2 concentration (ppm). The figures in the third column show
465	γ as a function of time (year) and in the fourth column as a function of temperature (°C). GPP,
466	NBP, and fgco2 are positive to the surface, R_A and R_H are positive to the atmosphere. We use
467	data extended to 2300 for IPSL-CM6A-LR. In the first and third columns, the years of peak
468	atmospheric CO_2 concentration and CO_2 growth rate are indicated by vertical black and blue
469	dashed lines, respectively.
470	5.3 Magnitudes of carbon cycle feedbacks under SSP5-3.4-OS
471	Apart from CNRM-ESM2-1, the strength of the β feedback parameter by ESMs is similar
472	over land and ocean, the strength of the negative γ parameter is larger over land than over ocean
473	(Figures 4a and 4b). The magnitude of global transient γ_{land} at the maximum exceeds γ_{ocean} nearly
474	1.5 times in IPSL-CM6A-LR, 2–3 times in CanESM5 and UKESM1-0-LL, and 10–20 times in

475 CNRM-ESM2-1 and MIROC-ES2L. This agrees with a study based on the idealized 1% CO₂ 476 increase $2 \times CO_2$ and $4 \times CO_2$ scenarios (see Table A1 of Arora et al., 2020) and persists in both 477 ramp-up and ramp-down stages of overshoot. The inertia of the Earth system causes an increase 478 in the absolute values of β and γ after the peaks of CO₂ and temperature, i.e., more positive β and

479 more negative γ (Figure 4).

480 IPSL-CM6A-LR is the only ESM that included both extended to the 23rd century BGC 481 and COU simulations that are necessary for the calculation of β and γ . At the end of the 23rd 482 century, CO₂ concentration is around 398 ppm and air temperature warming relative to pre-483 industrial value is around 1.9 °C. This ESM, unlike others, estimated nearly constant γ_{land} . The 484 model outputs show a continued amplification of β_{ocean} and γ_{ocean} at a reduced rate after the 2150s and nearly constant β_{land} and γ_{land} after the 2150s (Figure S11). This behavior of β and γ translates into nearly steady states of land and ocean carbon fluxes (Figure 2). By the end of the 23rd century, land and ocean storages increase by 180 and 416 GtC relative to the preindustrial levels, respectively.

The LUC effects on the global carbon cycle feedbacks may be increasingly strong in the future mitigation pathways (see Section 4.3). The amplification of global β_{land} may be reduced due to the conversion of large areas to biofuel croplands. The impacts of LUC on the global γ_{land} are even more uncertain. This uncertainty should be tackled in future studies as well as in a possible future MIP study.

5.4 Decomposition of β_{land} and γ_{land} into the β and γ of their constituent gross fluxes 494 We decompose β_{land} and γ_{land} into the β and γ of their constituent gross fluxes, to 495 investigate the processes behavior before and after the peaks of CO₂ and temperature (Figures 4, 496 6, S14 and S15). β of GPP, R_A, and R_H (β_{GPP} , β_{RA} , and β_{RH}) exhibit similar behavior with a 497 nearly parallel change, albeit with an opposite impact on the land uptake (Figures 4 c-e). All 498 ESMs demonstrate a larger β_{GPP} than β_{RA} and β_{RH} together, which provokes positive β_{land} 499 500 feedback during the study period. Global values of γ_{GPP} , γ_{RA} , and γ_{RH} are positive, except for CNRM-ESM2-1, while they are negative in the equatorial region for most ESMs (Figure S16). 501 This means that warmer temperatures under the SSP5-3.4-OS do not inhibit photosynthetic 502 503 processes in the warm regions to a level that surpasses the benefits of warming on the global ecosystem. 504

505 Unfortunately, most ESMs used in this study did not include permafrost or vegetation fire 506 components. By considering permafrost emissions, which roughly speaking are equivalent to γ

becoming more negative, Gasser et al. (2018) estimated that to achieve the 2 °C target of the 507 Paris Agreement, the remaining emission budget is reduced by 16% for 0.5 °C overshoot and by 508 25% for 1 °C overshoot. CESM2-WACCM, the only ESM we considered that resolves the 509 permafrost active layer, did not have BGC simulation outputs under the SSP5-3.4-OS pathway at 510 the time of this analysis. While it would be extremely interesting to look at the carbon cycle 511 512 feedbacks simulated by this model, its land and ocean carbon uptake estimates nearly median temporal variation of the carbon uptakes among our five ESMs (Figure 2). Based on the 513 spatiotemporal variation of soil carbon storage by the model (Figure S6), we speculate that the 514 permafrost fluxes are not significant in this scenario. Although in CESM2-WACCM, after the air 515 temperature peaks in 2058 (Figure 2), the land pool loses soil carbon in the high latitudes, the 516 loss is mainly attributed to medium soil pool with residence time <100 years (not shown), and it 517 is compensated by vegetation greening in the region. The permafrost fluxes may become 518 significant for larger magnitudes of temperature overshoot, and it is necessary to explore 519 520 permafrost feedback under different overshoot pathways.

521 5.5 Spatial variation of transient carbon cycle feedbacks under overshoot

522 The spatiotemporal variation of the changes in β and γ parameters clarifies the inter-523 model differences (Figure 5). β_{ocean} strengthens during the ramp-down in the mid-latitudes of the 524 Northern Hemisphere and equatorial zone and increases over the Southern Ocean. In many areas 525 of β_{ocean} increase, γ_{ocean} also intensifies, perhaps, due to the increases in the ocean pool.



526



530 The spatial variation of β_{land} and γ_{land} is strikingly diverse among models. ESMs agree 531 that β_{land} is positive in the equatorial region, and it increases during the ramp-up but decreases 532 during the ramp-down. CanESM5and UKESM1-0-LL have negative β_{land} over mid-latitudes till 533 the 2040s that is compensated by the positive γ_{land} . The negative γ_{land} over tropics in MIROC-534 ES2L is maintained throughout the study period, although it keeps decreasing (Figure 5). The 535 negative β_{land} emerges due to the decrease of ΔC_{land} below the pre-industrial value before ramping back by the end of the 21^{st} century (Figures S3 and S12). The decrease in ΔC_{land} corresponds to the decrease in ΔC_{soil} in CanESM5, and ΔC_{veg} in MIROC-ES2L and UKESM1-0-LL.

539 The γ_{land} is positive in the high latitudes and negative in the equatorial regions, as estimated by all ESMs except for CNRM-ESM2-1. The distinct changes in CNRM-ESM2-1 in 540 the idealized scenarios were discussed by Arora et al. (2020) and attributed to the larger 541 542 nonlinearity effects compared to other models. The negative γ_{land} in CNRM-ESM2-1 emerges due to negative γ_{soil} , while γ_{veg} stays positive through the study period (Figure S13). After the 543 peak of air temperature, the γ_{land} is increasingly negative in the equatorial zone (probably due to 544 drying, Figure 5b). Overall, our results imply that the amplification of the β_{land} after overshoot is 545 driven by the high latitudes, and the amplification of γ_{land} is driven by the equatorial regions. 546

547 5.6 Implication of changes in carbon cycle feedback metrics to the carbon fluxes under
548 overshoot

Due to the dependency of the β uptake on the CO₂ growth, it starts to decrease in the 549 early 2040s, leading to the peaks of the land and ocean uptakes in 2040s concurrent with the 550 551 peak of CO_2 growth rate (Figures 6a and 6b). The γ uptake peaks later due to temperature change lagging behind the atmospheric CO₂ change. Although the values of β and γ parameters (>0 for β 552 and <0 for γ) increase after the peaks of CO₂ and temperature, opposing each other, the total γ -553 driven loss of carbon is smaller than β gain at least till the end of the 21st century. The changes in 554 the carbon cycle are dominated by β rather than γ . While existing studies show that during the 555 ramp-up period, the positive contribution of the β is larger than the γ -driven loss (Arora et al., 556 2020), we demonstrate here for the first time that this remains valid for the ramp-down period 557 under SSP5-3.4-OS based on the five CMIP6 ESMs under consideration. 558

- 559 Apart from CNRM-ESM2-1 that has positive γ_{ocean} , ESMs show that the amplification of 560 β_{ocean} and γ_{ocean} during the ramp-down period cause the ocean to uptake more carbon compared to
- 561 if β_{ocean} and γ_{ocean} were fixed at the level of the peaks of CO₂ concentration and temperature. All
- 562 models agree that amplification β_{land} and γ_{land} lead to a larger cumulative land carbon uptake by
- the year 2100 under the SSP5-3.4-OS pathway.





Figure 6. Breakdown of land and ocean carbon uptakes to the contributions of β and γ (GtC year⁻ ¹) as a function of time, CO₂ concentration, and temperature. Contributions are calculated as

567	yearly change of $\beta \times \Delta CO_2$ and $\gamma \times \Delta T$ for (a) ocean carbon uptake fgco2, (b) NBP, (c) GPP, (d)
568	R_A and (e) R_H . The figures in the first column show β as a function of time (year) and in the
569	second column as a function of CO_2 concentration (ppm). The figures in the third column show γ
570	as a function of time (year) and in the fourth column as a function of temperature (°C). GPP,
571	NBP, and fgco2 are positive to the surface, R_A and R_H are positive to the atmosphere. We use
572	extended to 2300 data for IPSL-CM6A-LR In the first and third columns, the years of peak
573	atmospheric CO_2 concentration and CO_2 growth rate are indicated by vertical black and blue
574	dashed lines, respectively. The markers "*" and "×" indicate the periods before and after the
575	peak of CO ₂ concentration in 2062, respectively.

576 6 Conclusion

This study investigated the carbon cycle response of the six CMIP6 ESMs to the 577 578 temperature overshoot under the SSP5-3.4-OS pathway. The land and ocean continue to remove carbon from the atmosphere at least for 50 years after the peak of the CO₂ growth rate. They only 579 turn to a source afterward in the first half of the 22nd century for a short period and become a 580 weak sink later, i.e., reach a new steady-state. From the perspective of the carbon cycle feedback 581 framework, the land and ocean act as a carbon sink during both ramp-up and ramp-down stages 582 of overshoot in the 21st century because the β carbon gain $\beta \times \Delta CO_2$ is large than $\gamma \log \gamma \times \Delta T$ 583 under the considered pathway. 584

The decrease in the land and ocean uptakes occurs immediately after the start of mitigation efforts, and before the peaks of CO_2 concentration and temperature. The decrease in ocean uptake is driven by the dependency of the ocean sink on the CO_2 growth rate. Both land and ocean carbon uptakes show a strong nearly linear dependency on the CO_2 growth rate with the hysteresis behavior after the peak of the CO_2 increase. The decrease in land uptake is driven by the net effect of the decreasing rate of GPP increase and the increase in TER due to delayed warming after CO₂ concentration change. Besides, land-use change emissions induced by the broad expansion of biofuel crops in SSP5-3.4-OS contribute to the early peak of land uptake. This finding suggests that the choice of negative emission approaches is important and may affect the overall global carbon uptake (Jones et al., 2010; 2016a).

596 Despite differences, CMIP6 ESMs agree on the amplification of the carbon cycle 597 feedback parameters after the peaks of atmospheric CO₂ concentration and temperature due to 598 the inertia of the Earth System. The ESMs show that β becomes more positive and γ more 599 negative. The increase in feedback parameters after the peaks of CO₂ concentration and 590 temperature reflects the decreasing yet persisting carbon uptake by the ocean and land during the 591 ramp-down phase. Land and ocean continue to take up carbon (even though at a decreasing rate) 592 at a rate larger than expected from linear behavior.

The amplification of carbon cycle feedback parameters influences the overall uptake by land and ocean under mitigation scenarios and thus affects the ability of the Earth System to return to the temperature target after an overshoot. We encourage future studies to investigate the consequences of amplification of feedback parameters under different overshoot pathways to understand what this means in the mitigation context.

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- 612 simulations are available from the CMIP6 archive (<u>https://esgf-node.llnl.gov/search/cmip6</u>). Data
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- 614 CarbonTracker2019 via http://carbontracker.noaa.gov CAMS via
- 615 <u>https://apps.ecmwf.int/datasets/data/cams-ghg-inversions/</u>, the IIASA database via
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627 Author contributions

K. Tanaka conceived the research with input from O.B. and PCi. I.M. led the study, conducted
the analysis, and generated all figures and tables. PCa and K.Tachiiri performed additional Earth
system model simulations. I.M. and all co-authors discussed the results. I.M. drafted the
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632 **Conflict of Interest**

The authors do not declare any competing interests.

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Earth's Future

Supporting Information for

Carbon cycle response to temperature overshoot beyond 2 $^\circ\mathrm{C}$ – an analysis of CMIP6 models

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Contents of this file

Table S1 and figures S1 to S15

Introduction

This supporting information contains a table and fifteen figures.

ESM	IPSL-CM6A- LR	CNRM- ESM2-1	CanESM5	MIROC- ES2L	UKESM1-0- LL	CESM2- WACCM			
piControl	r1i1p1f1	r1i1p1f2	r1i1p1f1, r1i1p2f1	r1i1p1f2	r1i1p1f2 (parent to r4)	r1i1p1f1			
historical	r1i1p1f1 (1910)	r1i1p1f2 (1850)	r1i1p1f1 (5201)	r1i1p1f2 (1850)	r4i1p1f2 (1960)	r1i1p1f1 (55)			
ssp534-over	r1i1p1f1	r1i1p1f2	r1i1p1f1	r1i1p1f2	r4i1p1f2	r1i1p1f1			
ssp585	r1i1p1f1	r1i1p1f2	r1i1p1f1	r1i1p1f2	r4i1p1f2	r1i1p1f1			
hist-bgc	r1i1p1f1 (1910)	r1i1p1f2 (1850)	r1i1p2f1 (5550)	r1i1p1f2 (1850)	r4i1p1f2 (1960)				
ssp534-over- bgc	rli1p1f1	r1i1p1f2	r1i1p2f1	r1i1p1f2	r4i1p1f2				
ssp585-bgc	r1i1p1f1	r1i1p1f2	r1i1p2f1	r1i1p1f2	r4i1p1f2				

Table S1. Ensemble members used in each experiment and each model

Values in the bracket indicate the branching year from the piControl.



Figure S1. Time series of CO₂ concentration (ppm), CO₂ growth rate (scaled) and corresponding (a) CO₂ emissions (GtC year⁻¹) and (b) cumulative CO₂ emissions (GtC) by REMIND-MAgPIE from input4MIP for SSP-5-3.4-OS experiment. Emission data are from the Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis (IIASA) database at <u>https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome</u>. Fossil fuel emission data prior year 2005 are from the GCB2019 data set.



Figure S2. Time series of changes in global land biomass, land (NBP), and ocean carbon uptakes in the piControl experiment before (a) and after (b) pre-processing.



Figure S3. Mean land carbon pool sizes in piControl by six earth system models in fully and biogeochemically coupled simulations of SSP5-3.4-OS experiment (a). Time series of land carbon pools and cumulative ocean flux anomalies from piControl (b). Solid lines indicate COU run, and dashed lines indicate BGC run.



Figure S4. An evaluation of Earth system models (ESMs) against observational data set by Ciais et al. (2020). (a) fLUC, (b) NPP, (c) R_H , and (d) NBP absolute value with associated uncertainty at nine RECCAP regions in 2000-2009.



Figure S5. Time series of the growth rate of air temperature and by six earth system models and CO_2 concentration in SSP5-3.4-OS experiment (a). Rates of change in air temperature are given as a 10-year moving average. The surface air temperature changes relative to 1850–1999 mean versus cumulative compatible fossil fuel emissions in the SSP5-3.4-OS pathway (b). The slope of the curves is the transient climate response to cumulative emissions (TCRE).



Figure S6. The spatiotemporal variation of zonal cumulative (a) ΔC_{land} , (b) ΔC_{soil} , (c) ΔC_{soil} , and ΔC_{ocean} (GtC) in 1900-2300 under SSP5-3.4-OS pathway. ΔC_{ocean} is calculated from cumulative flux fgco2 over time.



Figure S7. Panel (a) shows the time series of the derivatives of GPP, TER, fLUC (GtC year⁻²), CO2 concentration (ppm), and scaled CO2 growth rate. fLUC is missing in CanESM5 and MIROC-ES2L because model teams did not provide this variable. Panel (b) shows the spatial variation of the difference between the mean ocean and land uptakes (NBP and fgco2) in 2050–2060 and 2030–2040. Positive values indicate an increase in carbon uptake in a later period.



Figure S8. Time series of changes in CO₂ emissions simulated by REMIND-MAGPIE under SSP5-3.4-OS pathway.



2050–2060 and 2030–2040 mean bioenergy cropland area difference

Figure S9. Difference between the mean bioenergy cropland area in 2050–2060 and 2030–2040 based on the LUH2 data set.



Figure S10. The difference in (a) the carbon uptake and (b) land-use change emissions before and after the peak of CO_2 concentration is shown as ensemble means of six (four for fLUC) CMIP6 ESMs.



Figure S11. Carbon-concentration β (GtC ppm⁻¹), carbon-temperature γ (GtC °C⁻¹) feedback parameters and their contributions to the carbon fluxes (GtC year⁻¹) for (a) ocean fgco2, and land (b) NBP, (c) GPP, (d) R_A and (e) R_H as a function of time (year) extended till the year 2300 for IPSL-CM6A-LR under the SSP5-3.4-OS pathway.



Figure S12. The spatiotemporal variation of zonal cumulative land carbon pool (positive to land) in (a) BGC simulation, (b) COU simulation, and (c) COU-BGC difference.



Figure S13. The spatiotemporal variation of zonal cumulative (a) β_{soil} , (b) β_{veg} (GtC ppm-1), (c) γ_{soil} and (d) γ_{veg} (GtC °C⁻¹) calculated from corresponding land carbon pools. Positive values indicate a net sink.



Figure S14. The spatiotemporal variation of zonal cumulative (a) β_{GPP} , (b) β_{RA} , and (c) β_{RH} (GtC ppm⁻¹) is calculated from corresponding cumulative land carbon fluxes. Positive values indicate a net sink for β_{GPP} and a net source for β_{RA} and β_{RH} .



Figure S15. The spatiotemporal variation of zonal cumulative (a) γ_{GPP} , (b) γ_{RA} , and (c) γ_{RH} (GtC °C ⁻¹) calculated from corresponding cumulative land carbon fluxes. Positive values indicate a net sink for γ_{GPP} and a net source for γ_{RA} and γ_{RH} .