Current oceanic CO_2 uptake: The priming effect of biological carbon pumps

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Supplementary Material

1. Supplementary Methods

UVic ESCM

All transient (year 1765 to 2100) model runs presented in this paper are simulated with an ocean-sea-ice-atmosphere version of the University of Victoria Earth System Model of intermediate complexity (UVic) version 2.9 [*Keller et al.*, 2012; *Weaver et al.*, 2001] supplemented with additional model code to carry out idealised biogeochemically-only coupled (BGC) experiments (see below). The fully coupled Earth System model was spun up under constant preindustrial (Holocene) conditions (pCO_2=278, orbital forcing of year 1765) for a total of 16000 years, thereafter the terrestrial and vegetation model was turned off and a 1500-year drift run with conserved carbon inventory was performed with the oceanic (incl. sea ice) and atmospheric model (dubbed ‘no-land model’ in the following) with prescribed monthly mean wind forcing from NCAR/NCEP climatological data. Starting from the state at the end of the drift run, we perform 6000-year spin-up experiments for the model variants noBioPumps, noTissue, no$CaCO_3$ pumps, and noPumps prescribing the climate to that at the end of the no land drift run.

Technical implementation of model variants

The ocean biogeochemistry of model variant allPumps is essentially the one of the UVic 2.9 model version of [*Keller et al.*, 2012] tuned against observations of macronutrients, oxygen, total dissolved inorganic carbon (DIC) and total alkalinity (ALK) . In the model variant noBioPumps the sinks-minus-source terms of DIC and ALK related to the production and degradation of organic matter and the production and dissolution of $CaCO_3$ are ignored. In this model variant DIC and ALK are influenced by virtual fluxes associated to evaporation and precipitation, in addition, DIC is influenced by gas exchange with the atmosphere. In model variant noTissue pump the sinks-minus-source terms of the tracers DIC and ALK related to the production and degradation of organic matter are ignored while $CaCO_3$ processing, virtual fluxes, and (for DIC) gas exchange affect the tracers. For the model variant no$CaCO_3$ pump the sinks-minus-source terms of the tracers DIC and ALK related to the production and dissolution of $CaCO_3$ are ignored while organic matter processing, virtual fluxes, and (for DIC) gas exchange affect the tracers. Model variant noPumps is like noBioPumps, but we additionally turn off the effect of high-to-low latitude differences in surface ocean temperature and variations in surface salinity on CO_2-solubility and use instead the globally averaged preindustrial surface temperature and salinity for the computation of CO_2 solubility and Schmidt numbers during the model variant spin-up.

Emissions scenario

Transient model experiments presented here apply CO_2 emissions from fossil fuel burning and land use change consistent with the RCP 8.5 business-as-usual CO_2 emission scenario using forcing data from the RCP database (http://www.iiasa.ac.at; [*Meinshausen et al.*, 2011]). For the purpose of our no-land-model experiments emission data are corrected, however, for net land fluxes diagnosed from a fully coupled UVic Earth System run. The resulting CO_2 emissions (dubbed RCP85-star forcing) applied to the ocean + atmosphere model add up to 1970 Gt C between 1765 and 2100. Consequently, atmosphere and ocean warming in the fully coupled no land transient experiment is consistent with the respective warming in the fully coupled with land experiment. We note that non-CO_2 greenhouse gases or aerosols are not considered in our idealized model experiments.

BGC and COU* model experiments

The concept of fully coupled (COU), biogeochemically coupled (BGC) and radiatively coupled (RAD) model experiments has been introduced by [*Friedlingstein et al.*, 2006] and is now used widely in the climate community (e.g. [*Arora et al.*, 2020]) in order to decompose effects from CO_2-concentration and carbon-climate feedbacks on land and in the ocean. Usually this approach is applied to 1-percent-per-year-CO_2 increase experiments or sometimes to historical or RCP 8.5 / SSP585, i.e. CO_2 concentration driven simulations (compare e.g. CMIP6 data holdings, e.g. https://esgf-data.dkrz.de/search/cmip6-dkrz/; 1ptCO2-bgc, 1ptCO2-rad, hist-bgc, hist-rad, ssp585-bgc, ssp585-rad). We adopt and slightly modify this concept here for our transient model experiments with CO_2 emissions carried out with the UVic model.

BGC experiments: Starting from the end of its respective spin-up, we perform BGC experiments for the time period 1765 to 2100 for each model variant. Our BGC experiments apply the emissions from the RCP85-star forcing (see above), while keeping the climate constant at preindustrial conditions. In the UVic model this can be easily done by fixing the pCO_2 value used in the computation of radiative forcing at the preindustrial value. Since we use a no-land model version there is no additional climate change from e.g. CO_2-fertilization effects on land and associated albedo changes.

COU* experiments: We also perform coupled model experiments for all model variants. These coupled experiments apply emissions like in BGC and at the same time force the model's climate with a transient climate forcing due to increasing atmospheric CO_2. Considering the attribution objective of our study (see introduction), we adopt the pCO_2^{atm}-climate forcing derived from the allPumps transient model run to all model variants. In the UVic model this can be done by reading in pCO_2 model output from a fully coupled experiment (see [*Koeve et al.*, 2020]) at model run time and apply these pCO_2 values for the computation of the models' radiative forcing. In order to indicate the differences to the standard COU experiments (e.g. [*Arora et al.*, 2020]), our experiments are denoted COU* experiments. This approach ensures that COU* experiments of all model variants (e.g. noTissue, $noCaCO_3$) feel the same climate change forcing. In the case of the noPump model globally averaged SST and SSS are computed at every model time step and applied for the computation of CO_2 solubility and Schmidt numbers in order to turn off the effect of high-to-low latitude differences in SST and SSS on CO_2 solubility and gas exchange. Global mean SST increases according to the changing climate.

We use the COU*-BGC model difference to quantify carbon-climate feedbacks.

2. Supplementary Results

Default model behaviour

In the allPumps model variant the RCP85-star forcing causes the atmospheric pCO_2 and surface air temperature to increase to 943 ppmv and by 3.72 °C, respectively, until year 2100. The ocean takes up a total of 541 Gt C, equivalent to 27.5% of the cumulative emissions to the atmosphere. In a control (drift) run (no CO_2 emissions) carried out over the same time period, atmospheric pCO_2 was 275.1 ± 0.05 ppm and surface air temperature 13.02 ± 0.03 °C. (see [*Koeve et al.*, 2020], SI for details). A slightly lower than observed preindustrial allPumps atmospheric pCO_2 (275.1 ppm vs. 278 ppm) develops when using a freely evolving atmosphere after branching off the ocean-atmosphere model version from the fully coupled Earth System model during spinup. Net carbon uptake during the historical period (1870 to 1995) in our allPumps model variant is 96.6 Pg C, which compares well with the CMIP5 model mean (± 1std) of 97 ± 8 Pg C) [*Frölicher et al.*, 2015]. Both the CMIP model mean and our model's marine DIC inventory change appear biased low, compared with several data bases estimates, which however, may be an artifact of considering different start dates for the integration ([*Bronselaer et al.*, 2017]). In our model, integrating the DIC inventory change between year 1765 and 1994 yields 107 Pg C, being in good agreement with data based estimates (106 ± 17 Pg C, [*Sabine et al.*, 2004]; 114 ± 22 Pg C, [*Khatiwala et al.*, 2009]).

Robustness of priming and carbon climate feedback estimates

During the spin-up experiments of model variants used in our study, we intentionally exclude any climate feedbacks on atmospheric pCO_2 by prescribing the climate to the one of the allPumps. Using an ocean-sea-ice-atmosphere version of UVic 2.9 only, we also exclude any potential carbon concentration or carbon-climate feedback from the land system. We exclude these feedbacks in order to have a clear and straightforward experimental design without cross-system interactions and interferences.

We decided for this approach, since the major objective of this paper is to better understand why the ocean (represented by this specific model) takes up a specific amount of C^{anth}, and how biology (soft tissue pump, $CaCO_3$ counter pump) primes the net uptake of C^{anth} in the full model (allPumps). The identified contributions add up surprisingly linear (see main text, section Priming of C^{anth} uptake), given the non-linearities of the seawater CO_2-system.

Including also feedbacks (e.g. allowing for different climates fully consistent with pCO_2^{atm} at the end of the spinup) would have compromised this intention and attribution of fraction of C^{anth} uptake of the full model to the different marine carbon pumps would be ambiguous. For the second objective of our paper (quantifying the role of marine carbon pumps to carbon-climate feedbacks) we assume that the feedbacks may be somewhat truncated in our COU* (coupled) experiments compared to experiments which starts from a climate-consistent spinup (s.a.). However, computing carbon-climate feedbacks from the difference COU*-BGC only makes sense if both experiments start from identical states with respect to climate, circulation and hence tracer distributions.

Below we explore the impact of the described simplifications for one example. For the noBioPumps case sensitivity spin-up experiments allowing for feedbacks where performed (Tab. S4).

First, a noLand noBioPumps experiment is done in which the increasing atmospheric pCO_2, which results from stopping the biological carbon pumps, affects the radiative forcing and causes an increase in surface atmospheric temperature (SAT). After 6000 years, SAT has increased in this noBioPumps experiment by about 2.6 °C. This experiment with carbon-climate feedbacks reveals an atmospheric pCO_2 of 450 ppm at the end of the spinup, i.e. 3% larger compared to the respective default case used here (437 ppm).

Second, a full Earth System model spinup for the noBioPumps variant including climate feedbacks and land biosphere feedbacks is done by including the UVic terrestrial and vegetation model (TRIFFID, [*Meissner et al.*, 2003]). In this experiment increasing atmospheric pCO_2 from stopping the marine biological carbon pumps further causes a CO_2 fertilization effect on land plants and associated changes in the biosphere. Until the end of this spinup the terrestrial biosphere has taken up a total of 266 Pg carbon originally emitted from the ocean. This causes in turn a lower atmospheric carbon of 424 ppm (i.e. 3% lower compared to the default experiment). Given that a noBioPumps spin-up with the full Earth system model subject to all marine, terrestrial and atmospheric feedbacks included in UVic 2.9 has an atmospheric pCO_2 very similar to the version used in this study (437 ppm), the priming effects presented here for an idealised model version can be considered representative of the full Earth system model.

3. Supplementary Discussions

Impact of boundary conditions during spinup

We carry out an additional set of model experiments with the model variant noBioPumps_fixed in which we adopt the approach used in [*Sarmiento and Le Quéré*, 1996] (see main text for rational). Similar to their 'solubility-only model' our experiment noBioPumps_fixed has been spun up with prescribed atmospheric pCO_2 and only the transient experiment is carried out with a freely evolving atmospheric pCO_2 and the same CO_2-emissions used for the other model variants.

The preindustrial state in noBioPumps_fixed differs considerably from that of our noBioPumps variant. First, the global DIC inventory of the ocean and also of ocean-plus-atmosphere are much lower. Being forced with the pre-industrally observed pCO_2^{atm}, the ocean+atmosphere CO_2-inventory of noBioPumps_fixed is artificially reduced by about 1828 Pg C, compared with the allPumps and noBioPumps experiments, the later two showing identical ocean+atmosphere CO_2 inventories due to mass conservation (Tab. 3). This artificial loss in CO_2 inventory is exclusively from the ocean, where the global mean DIC profile of noBioPumps_fixed is much reduced compared to noBioPumps (Fig. 4a). This disappearance of carbon from the simulated Earth-System is a consequence of the redistribution of carbon and alkalinity in noBioPumps_fixed towards the surface ocean (compared with allPumps). Elevated surface DIC (Fig. 4a) and alkalinity (Fig. 2b) effect a pCO_2^{sw} being larger than the prescribed pCO_2^{atm}. Consequently, the ocean loses CO_2, in order to rectify the ocean-atmosphere pCO_2-difference towards the equilibrium state where both agree. However, there is no equivalent atmospheric gain counterpart, since atmospheric pCO_2 is prescribed. Consequently, carbon disappears from the Earth system. This violates the concept of mass conservation with implications for the regional patterns of the surface CO_2-buffer.

The surface DIC reduction causes the DIC anomaly noBioPumps_fixed – allPumps in the surface ocean to be smaller than the respective anomaly noBioPumps – allPumps (see Fig.

S2a). This fosters a larger preindustrial $\delta DIC/\delta pCO_2$ buffer factor in noBioPumsp_fixed compared with noBioPumps (Fig. 4b). Forced by the prescribed atmospheric pCO_2-boundary condition, the zonally averaged $\delta DIC/\delta pCO_2$ in noBioPumps_fixed is actually very similar to that in allPumps over much of the ocean, which, for identical circulations in the transient BGC experiments, would suggest identical C^{anth} uptake, i.e. no effect of biological carbon pumps on C^{anth} uptake. It is only for the elevated zonally average $\delta DIC/\delta pCO_2$ in the high latitudes in noBioPumps_fixed, compared with allPumps (Fig. 4b), that the C^{anth} uptake in noBioPumps_fixed differs from that of allPumps. The forced shift towards elevated high latitude $\delta DIC/\delta pCO_2$ in noBioPumps_fixed, compared with allPumps, gives rise to an apparent negative priming impact of biological carbon pumps on marine C^{anth}-uptake (Fig. 4c), similar to what has been found in the 'solubility-only' experiments by [*Sarmiento and Le Quéré*, 1996].

[*Sarmiento and Le Quéré*, 1996] attributed the difference in C^{anth} uptake of their full model (similar to our allPumps) and their 'solubility-only' model (our noBioPumps_fixed), i.e. the negative priming effect of the combined biological carbon pumps, mainly to the impact of the $CaCO_3$ counter pump on surface alkalinity in the full model, affecting a reduction of the surface CO_2-buffer. We also see such a reduction of the surface alkalinity due to the $CaCO_3$ pump in our experiments (Fig. 2b, the orange line represents noBioPumps and noBioPumps_fixed, alike).

However, this is not the process that controls the C^{anth}-uptake anomaly in experiments with our different model variants noBioPumps and noBioPumps_fixed, compared to the allPumps case (see Fig. 4c). Instead this difference is controlled by whether the preindustrial $\delta DIC/\delta pCO_2$ is allowed to decrease according to the elevated atmospheric pCO_2^{atm} consistent with a world without biological carbon pumps (experiment noBioPumps, Tab. S1) or forced by a prescribed pCO_2^{atm} (experiment noBioPumps_fixed) towards a $\delta DIC/\delta pCO_2$ being even higher than the one of allPumps (Fig. 4b).

In conclusion, we find that the boundary conditions during spinup (forced vs. freely evolving atmospheric pCO_2) determine the preindustrial surface CO_2-buffer capacity and hence the transient C^{anth}-uptake response. Consequently, the BGC transient experiment carried out starting from that end-of-spinup state of noBioPumps_fixed shows an enhanced C^{anth} uptake of 642 Pg C (Tab. S3), i.e. more, not less, than the allPumps experiment. This enhanced C^{anth} uptake, however, is born from the 'artificial' nature of the respective spinup experiment, its violation of mass conservation, and its falsely enhanced surface CO_2-buffer.

Compensating carbon-climate feedbacks associated with biological carbon pumps

A changing climate may cause a change of marine carbon pumps which then may feed back on atmospheric pCO_2. Studies from climate model inter-comparison projects, f.e., have suggested that increasing ocean surface warming and a resultant more stably stratified ocean that lessens the resupply of nutrients from the interior ocean will result in a decrease of the soft-tissue pump in low to mid latitudes, suggesting a potential positive feedback to atmospheric pCO_2 [*Cabre et al.*, 2015; *Laufkötter et al.*, 2016; *Laufkötter et al.*, 2015], thereby potentially reducing the strength of the soft-tissue pump in a warming world.

The same time, though, a more stably stratified ocean also weakens the ventilation of the ocean interior, resulting in a more effective storage of respired carbon (DIC from the degradation of organic matter) in the ocean interior and thereby increase the DIC that is locked away from an exchange with the atmosphere by the soft tissue pump [*Koeve et al.*, 2020]. Indeed, the increased "oxygen dept" that goes along with an increase in the residence time of the interior ocean locking away the degradation products of organic matter degradation more efficiently, has driven ocean deoxygenation in the deep ocean over the past decades [*Schmidtko et al.*, 2017] .

Modelling studies revealed that the latter process dominates over the decrease in export production in high CO_2-emission scenarios until the end of this century [*Bopp et al.*, 2002; *Koeve et al.*, 2020]. The integrated impact of a changing soft-tissue pump hence appears to be a negative feedback to atmospheric pCO_2 and climate [*Koeve et al.*, 2020]. The strength of this feedback, however, is difficult to quantify in the presence of the invasion of huge amounts of anthropogenic CO_2 and an eroding surface ocean buffer ([*Bopp et al.*, 2013; *Fassbender et al.*, 2017]; Fig. 2c). The eventual role of a changing $CaCO_3$ pump is even less certain. Here, ocean acidification may be an additional driver (of change), compared to warming and circulation change ([*Hofmann and Schellnhuber*, 2009; *Segschneider and*

Bendtsen, 2013] though in a complex manner via decreasing $CaCO_3$ production and export combined with changing ballasting effect and organic matter flux attenuation. The net effect of changes in the biological carbon pumps on net CO_2-uptake is hence uncertain even in terms of the sign, i.e. whether it forms a weak positive or negative feedback to atmospheric CO_2.

In the presence of the massive flux of anthropogenic CO_2 entering the ocean as a consequence of the partial pressure gradient between increasing atmospheric concentrations and an ocean at large still in equilibrium with the preindustrial atmosphere, however, the impact of changes of biological carbon pumps on net CO_2 uptake by the ocean is difficult to quantify and probably small [*Koeve et al.*, 2020].

4. Supplementary References

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Supplementary Tables

Tab. S1: Maximum impact of biological carbon pumps on atmospheric pCO_2 as derived from published idealized model experiments.

	ΔpCO_2 (ppm)	Integration (years)	Reference	Remarks
noBioPumps	+ 170; + 250	Steady state	[*Sarmiento and Orr*, 1991], their Tab. 1	Various box models
noBioPumps	+ 184	Steady state	[*Shaffer*, 1993]	HILDA-box model (ocean-atm)
	+ 170	Steady state	[*Sarmiento and Bender*, 1994]	Box model
noBioPumps	+ 225	250	[*Maier-Reimer et al.*, 1996]	ocean-atmosphere model
noBioPumps	+ 146	10000	[*Kvale et al.*, 2021]	Uvic Earth System model, including land biosphere, including climate feedbacks
noBioPumps	+ 160	6000	this study	Uvic model, in ocean-atm mode; climate fixed at preindustrial
noCaCO3	- 12	10000	[*Kvale et al.*, 2021]	Uvic Earth System model, including land biosphere, including climate feedbacks
noCaCO3	- 31	6000	this study	Uvic model, in ocean-atm mode; climate fixed at preindustrial
noTissue	+ 221	6000	this study	Uvic model, in ocean-atm mode; climate fixed at preindustrial
noPumps	+ 440	Steady state	[*Volk and Hoffert*, 1985]; [*Sarmiento and Orr*, 1991], their Tab. 1	Box model
noPumps	+333	6000 years	this study	Uvic model, in ocean-atm mode; climate fixed at preindustrial; see text for details
FullyEfficient (all nutrients stripped off in the Southern Ocean)	-115	Steady state	[*Sarmiento and Bender*, 1994]	Box model
Fully Éfficient ('Ice age scenario', all nutrients stripped off from surface ocean)	-115	Steady state	[*Sarmiento and Toggweiler*, 1984]; [*Sarmiento and Bender*, 1994], their Tab. 1	Box model

noBioPumps: turning off soft tissue and $CaCO_3$ pumps; noTissue: turning off soft-tissue only; noCaCO3: turning off CaCO3 pump only; noPumps: turn of biological pumps and assume constant surface SST for CO_2 solubility. FullyEfficient refers to model studies which forced surface nutrients to zero, usually in nutrient restoring approaches. Integration (years) refers to the model integration time (spinup time). Note that we excluded publications, which, while giving huge estimates for the effect of turning of biological pumps, obviously violated mass conservation in their estimates.

Tab S2: Steady state atmospheric pCO_2 at the end of the spin up period. Cumulative ocean carbon uptake C^{anth} in the experiments with constant climate (BGC), and atmosphere to ocean carbon fluxes due to carbon-climate feedbacks. Fluxes (Pg C) are integrated between 1765 and 2100 and defined positive if the ocean takes up carbon.

Model variant	End-of-spinup pCO_2^{atm} (ppm)	C^{anth} uptake§ (Pg C)	Atmosphere to ocean CO_2 fluxes due to climate feedbacks$^{\$}$ (Pg C)
allPumps	275 *	596	-58
noTissue	498	402	-90
no$CaCO_3$	247	657	-59
noBioPumps	437	466	-88
noPumps	608	373	-68

§ from BGC transient experiments; $ from COU-BGC transient experiments; † from COU-COU_asesst runs; BGC=biogeochemically coupled, COU*=fully coupled (radiatively and biogeochemically); * a slightly lower than observed preindustrial allPumps atmospheric pCO_2 (275 ppm) is due to a freely evolving atmosphere when branched of the ocean-atmosphere model version from the fully coupled one during spinup (see Koeve et al., 2020 and Suppl Methods for details).

Tab. S3 Model variant noBioPump_fixed, i.e. a variant similar to the model variant noBioPumps, but spun up against a fixed atmospheric pCO_2 (275 ppm).

Model variant	End-of-spinup			C^{anth} uptake§ (Pg C)	Atmosphere to ocean CO_2 fluxes from climate feedbacks $^{\$}$ (Pg C)
	pCO_2^{atm} (ppm)	Inventory (ocean) (Pg C)	Inventory (oce+atm) (Pg C) †		
allPumps	275^{*}	37215	37801	596	-58
noBioPumps_fixed	275^{*}	35387	35973	642	-125
noBioPumps	437	36870	37801	466	-88

§ from BGC transient experiments; $ from COU-BGC transient experiments; † Ocean plus atmosphere inorganic carbon inventory, * a slightly lower than observed preindustrial allPumps atmospheric pCO_2 (275 ppm) is due to a freely evolving atmosphere when branching of the ocean-atmosphere model version from the fully coupled one during spinup

Tab. S4: End of spin-up (6000 years) atmospheric pCO_2 in sensitivity model experiments with model variant noBioPumps allowing for climate and/or land system feedbacks.

Sensitivity experiment (spinup)	pCO_2^{atm} (ppm)	Remarks
Default noBioPumps	437	No Land, climate fixed to preindustrial
wLand-noClim	397	With Land, climate fixed to preindustrial
noLand-wClim	450	No Land, climate feedbacks affect the ocean during spinup
wLand-wClim	424	With Land, climate feedbacks affect ocean and land during spinup

Supplementary Figures (captions)

Fig. S1. Surface ocean carbonate ion concentration in BGC experiments with different model variants. (a) Preindustrial zonally averaged surface carbonate ion concentration, (b) Global mean surface carbonate ion concentration between 1765 and 2100. Model variants (allPumps, black; noBioPumps, orange; noTissue, green; noCaCO3, red; noPumps, blue) are as indicated in the caption of Fig. S1 and described in more detail in Online Methods.