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Supporting Information for

Does export production measure transient changes of the biological carbon pump under global warming?

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Introduction

Here we provide Supplentary Methods (Text S1), Supplementary Figures (S1 to S7) which present details of our model experiments and two Supplementary Tables.

Text S1.

Supplementary Methods

UVic model

All transient (yr 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 idealised tracers of true oxygen utilization (TOU; [*Ito et al.*, 2004; *Koeve and Kähler*, 2016]) and ideal age [*England*, 1995; *Koeve et al.*, 2015]. The fully coupled Earth System model was spun up under constant Holocene conditions (pCO_2=278, orbital forcing of yr 1765), thereafter the land model was turned off and a 1500 yr drift run was performed with the oceanic (incl. sea ice) and atmospheric model with prescribed monthly mean wind forcing from NCAR/NCEP climatological data. Starting from the state at the end of the drift run, we perform a coupled simulation (**COUPLED**) under the RCP 8.5 business-as-usual CO_2 emission scenario, applying emissions from fossil fuels and land use change using forcing data from the RCP database (http://www.iiasa.ac.at; [*Meinshausen et al.*, 2011]), corrected, however, for net land fluxes diagnosed from a fully coupled UVic Earth System run. The residual CO_2 emissions (dubbed RCP85-star forcing) applied to the ocean + atmosphere model in COUPLED add up to 1970 Gt C between 1770 and 2100. We also perform a control run (**CTRL**) as a drift run (no CO_2 emissions) between yr 1765 and 2100. Atmospheric pCO_2 was 275.1 ± 0.05 ppm in the control run and surface air temperature was 13.02 ± 0.03 °C. The coupled atmosphere-ocean run COUPLED is characterized by a changing climate (the atmosphere warms by 3.72 °C; **Fig. S1b**), changing ocean circulation (as indicated by regional changes of the model's ideal age; **Fig. S2**) and an increase in atmospheric pCO_2 to 943 ppmv until yr 2100 (**Fig. S1a**). The ocean takes up a total of 542 Gt C, equivalent to 27.5% of the cumulative emissions to the atmosphere. Using the output of experiments COUPLED and CTRL, we diagnose the annual mean anomalies (COUPLED - CTRL) of sea surface temperature, SST, (x, y, and t dimensions), and oxygen sources-minus-sinks (O_2-sms), (x, y, z, and t dimensions). We modify the UVic code to allow for the assimilation of these anomalies and design a series of idealised experiments which combine the impact of global warming on biological rates including export and respiration and different possible intensities of warming-induced circulation changes (see Tab. S1 for details).

Experiments carried out

Starting from the experiments COUPLED and CTRL explained above and the diagnosed SST anomalies, we perform a series of experiments in which the oxygen flux between the ocean and the atmosphere does not feel the change in surface ocean temperature, hence $F_{O2} = F_{O2}^{biotic}$. In experiments #1 to #7 and #12 to #18, the annual mean sea surface temperature (SST) difference between COUPLED and CTRL has been assimilated at model run time for the computation of oxygen solubility and gas exchange. Air-sea oxygen flux is hence corrected for the solubility effect of global warming. Runs 8-11 have the physical conditions of CTRL, hence they do not need to assimilate SST for oxygen solubility explicitly.

Tab S1 gives an overview of the experiments carried out. We construct a range of potential responses of the biological carbon pump to climate change by combining four categories of experiments:

(a) Coupled ocean-atmosphere run (COUPLED_SST, #1 in Tab. S1, large black + in **Figs. 3, S5, S7**), in which changing biological rates as well as changing circulation both affect oxygen and TOU tracer values according to the RCP85star climate scenario. Oxygen (and TOU) sources and sinks in this run are computed prognostically.

(b) Coupled transient runs with changing climate and circulation (like in COUPLED_SST) where biological rates from CTRL are assimilated at model run time everywhere (COUPLED IMPOSE, #2 in Tab. S1) or in specified regions (experiments #3 - #6, see last column of Tab. S1 for details; red symbols in **Fig. 3, S5, S7**) are carried out. The assimilation procedure is adopted from [*Bopp et al.*, 2002; *Yamamoto et al.*, 2015], but modified as follows. The difference of local annual means (4D) of oxygen source-minus-sinks (O_2-sms) between COUPLED and CTRL is computed offline, stored to file, and assimilated at model run time to affect the oxygen and TOU tracer. The assimilation process differs for runs with climate change (runs 2-7) in comparison to CTRL-like runs (next section). In model run #2, the assimilation is carried out in order to compensate for changes occurring at model run time and, in the annual mean, causes the effect of biological rates on oxygen and TOU to be almost identical with CTRL (**Fig. S4b**). In this run, circulation changes only affect the oxygen and TOU tracer distribution. Runs #3 to #6 are variants of run #2, in which the assimilation is only carried out in specific regions, e.g. south of 40°S (run #3). Run #7 is a specific case in which O_2-sms is assimilated twice which provides an extreme simulation with inverted response of the biological processes on climate change.

(c) Control runs #8 to #11 (no climate change and no circulation change) to which we assimilate biological rates from COUPLED at model run time everywhere or in specified regions (dark blue symbols in **Fig. 3, S5, S7**) are carried out. Runs #8 to #11 have the climate and circulation of CTRL and assimilate the biological rate differences in order to impose the impact of transient changes of biological rates on oxygen (and the TOU tracer). In these runs only the (imposed) changes of biological rates cause the oxygen and TOU tracer distribution to change since circulation has no trend between 1770 and 2100 in CTRL. In run #8, the local annual mean difference of O_2-sms is added to the O_2-sms term emerging at model run time (see **Fig S4a**). In runs #9 to #11 assimilation of O_2-sms is restricted to specific regions, e.g. south of 40°S (run #9).

d) In addition to the main experiment COUPLED_SST with default circulation (large black + in **Figs. 3, S5, S7)**, we perform sensitivity experiments with modified vertical background diffusivity (# 12 to #18 in **Tab. S1**, small black + in **Figs. 3, S5, S7)**. Background vertical diffusivity has been varied between 0.5 and 0.05 cm^2/sec to simulate different ocean circulations similar to [*Duteil and Oschlies*, 2011; *Koeve et al.*, 2015]. The runs are based on respective spin-up, drift, and control runs. The annual mean anomalies of SST, derived from respective COUPLED and CTRL model experiments are assimilated at model runtime for the computation of oxygen air see exchange.

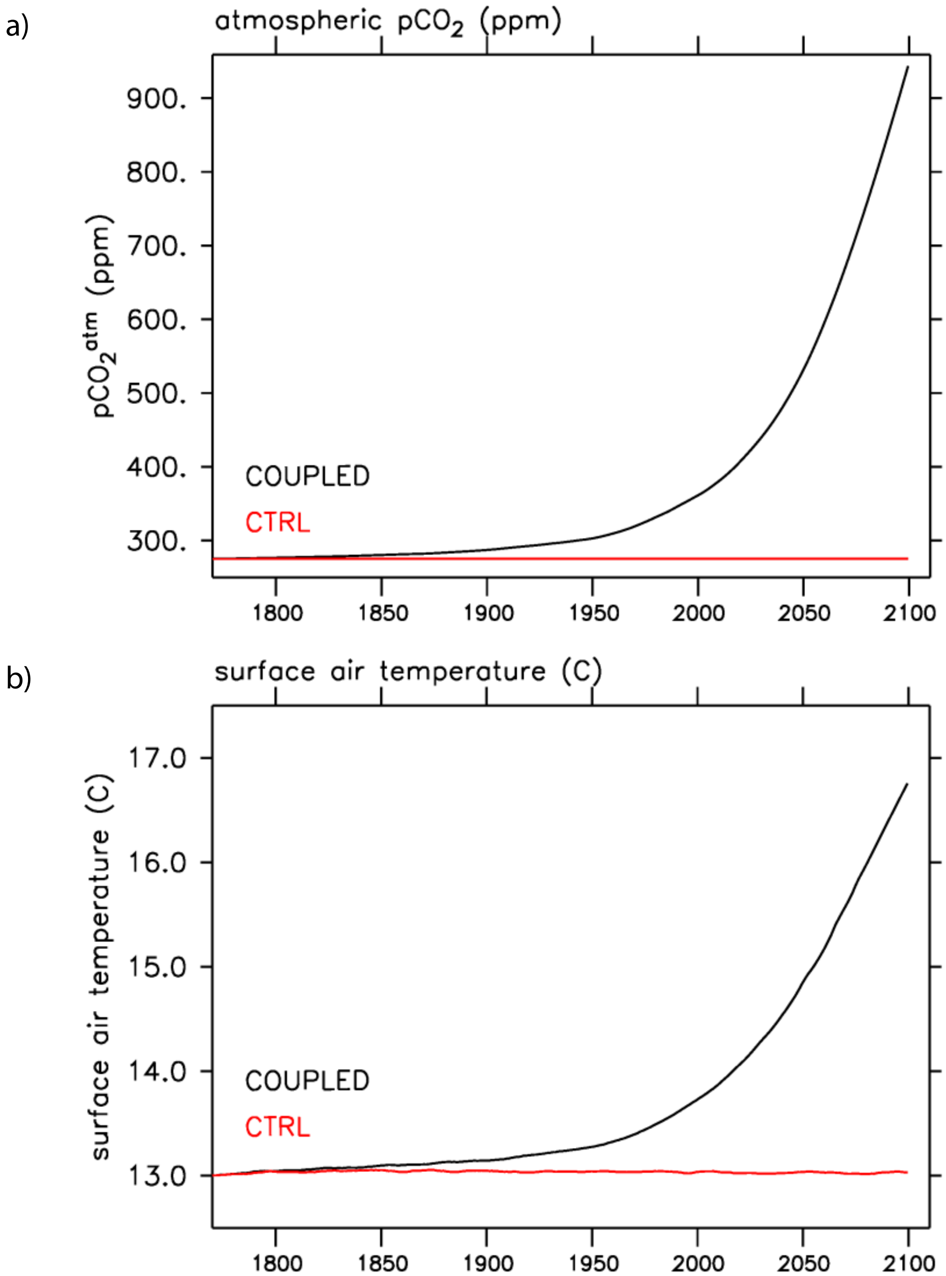
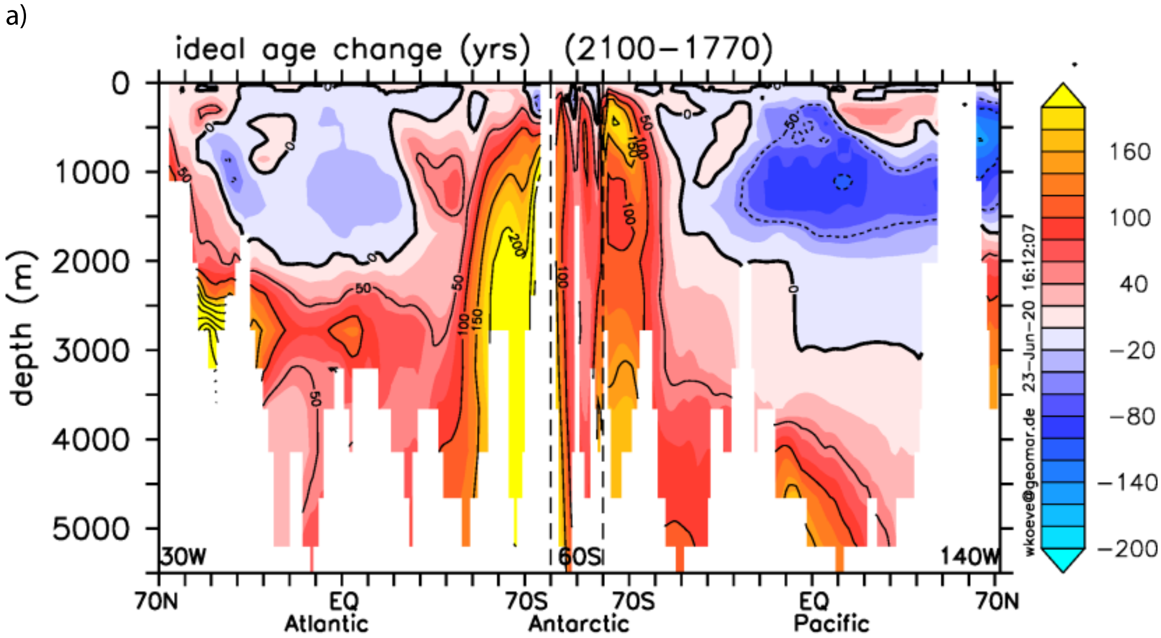


Figure S1. Transient atmospheric properties between years 1770 and 2100: (a) atmospheric pCO_2 (ppm) and (b) surface air temperature (°C) of run COUPLED (black solid lines) and CTRL (red solid lines).

a)



b)

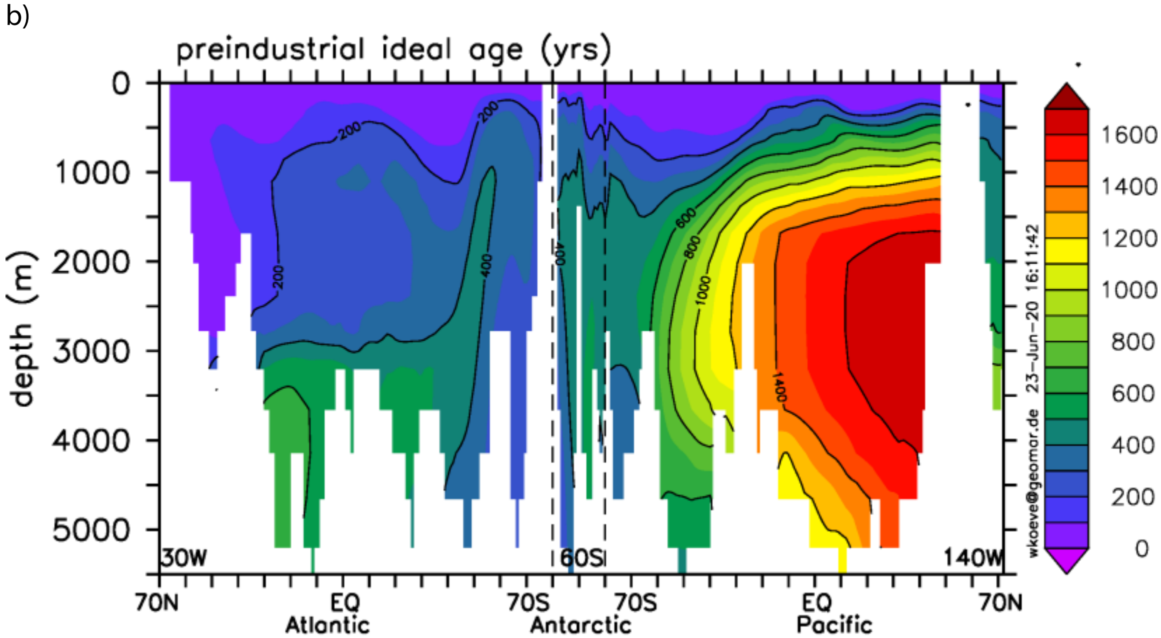
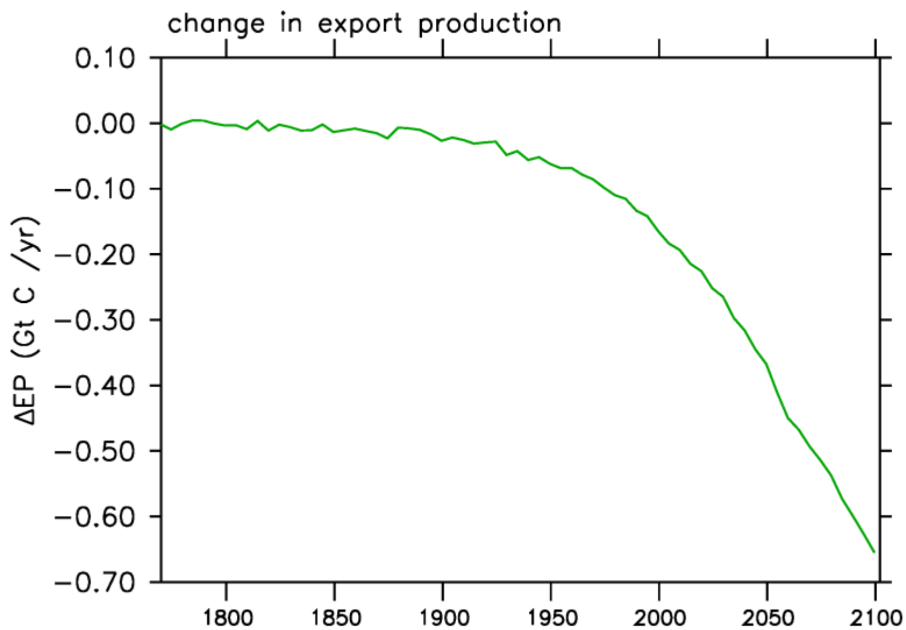


Figure S2. Ideal age (years) along a Atlantic Ocean – Southern Ocean – Pacific Ocean transect: (a) Age change in run COUPLED (2100-1770), (b) Age distribution in 1770 in run CTRL.

a)



b)

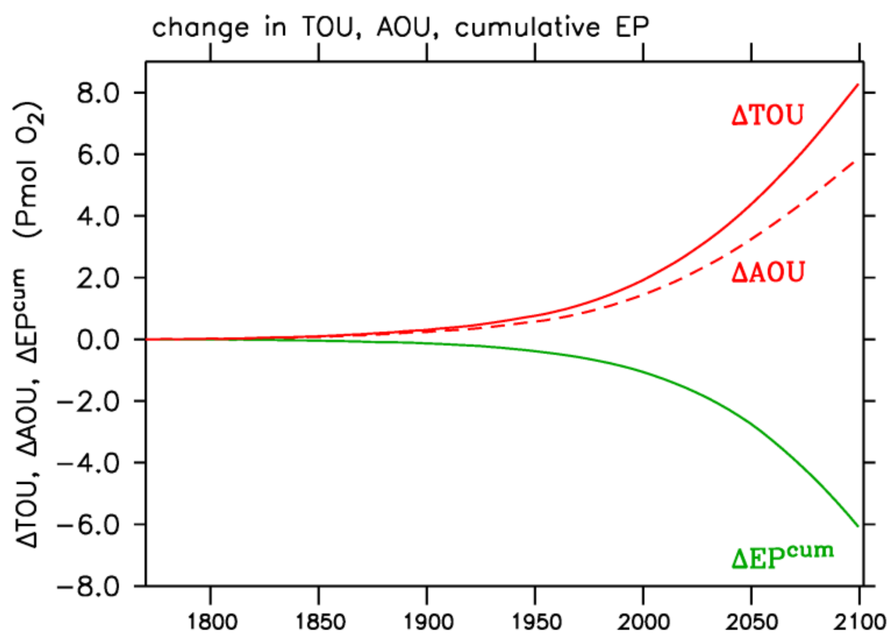


Figure S3. Transient evolution of (a) export production (Gt C / yr; z=130m), (b) cumulative export production (green solid), true oxygen utilization (TOU, red solid), and apparent oxygen utilization (AOU, red dashed). Note that the cumulative change in export production in (a) is presented in carbon units per year while the cumulative change in export production in (b) is given in equivalent oxygen units (Pmol O_2) to better compare against TOU and AOU changes. In (b) number given for TOU and AOU are global integrals below z=130m.

a)

b)

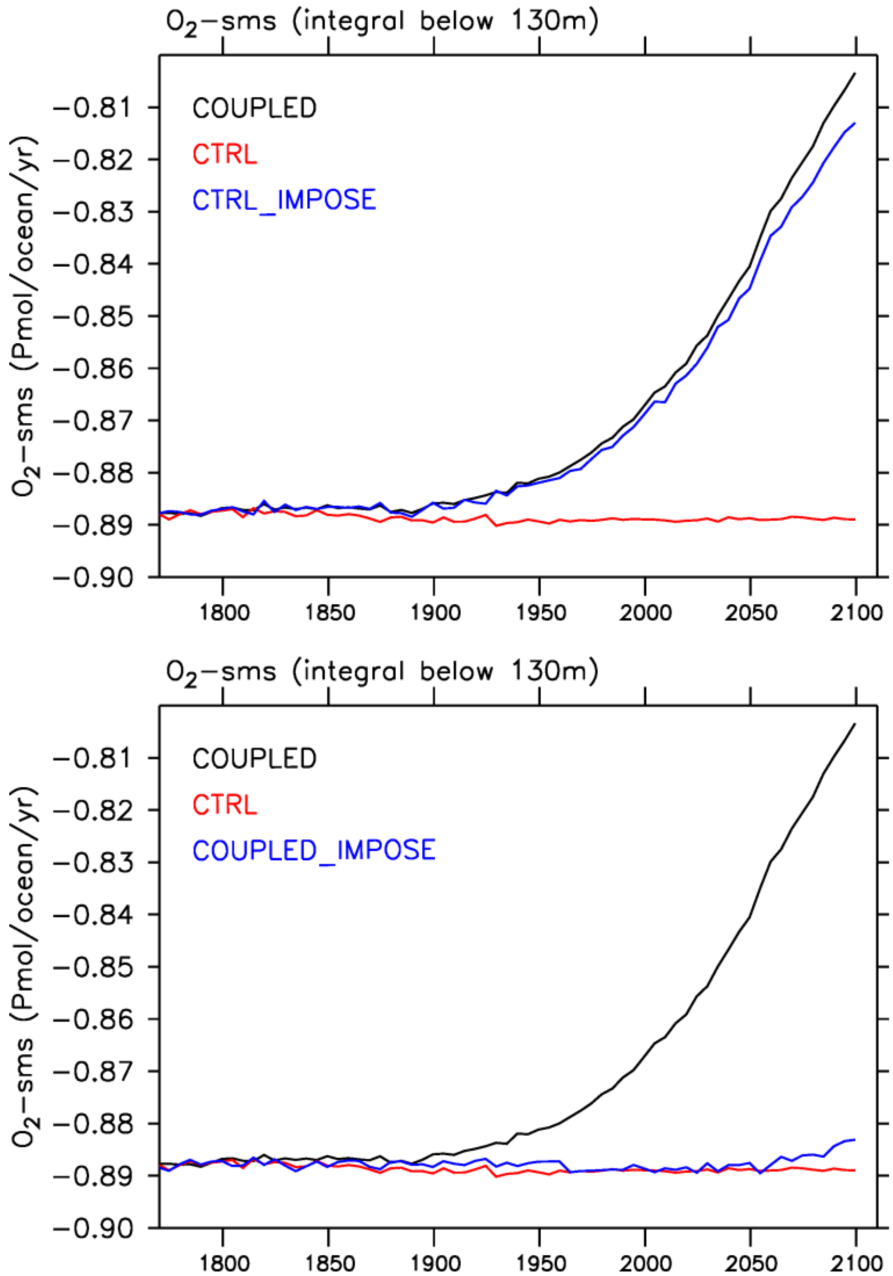


Figure S4. Globally integrated oxygen sinks-minus-sources in the ocean interior (z >130m) for runs COUPLED (black), CTRL (red), CTRL_IMPOSE (blue, panel a), and COUPLED_IMPOSE (blue, panel b).

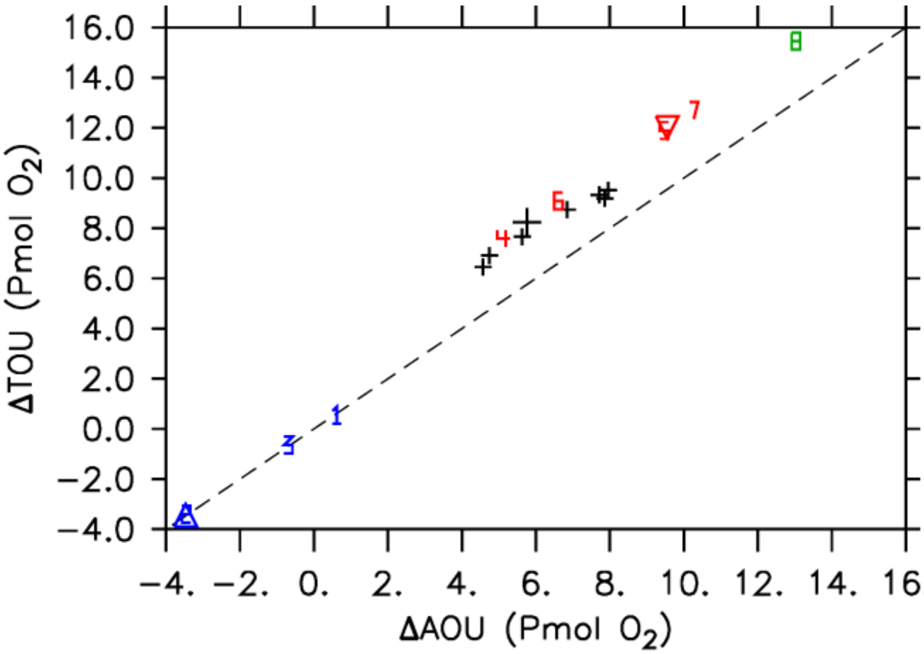


Figure S5. Transient change (2100 – 1770) of globally integrated true oxygen utilization (TOU) vs. apparent oxygen utilization (AOU) from model runs (Tab. S1) 1a to 7a, 8-11, and 12a to 18a. Note that AOU cannot be computed correctly for model runs 1-7 and 12-18 which apply SST assimilation for oxygen solubility and gas exchange computation, since the temperature at the time of gas exchange is not traced by an additional idealized tracer into the ocean interior in our model runs. Hence, we performed additional model runs (1a to 7a, 12a to 18a) without SST assimilation, but otherwise identical to runs 1 to 7 and 12 to 18, which are used for the comparison in this figure. Symbols are as in Fig. 2, respectively.

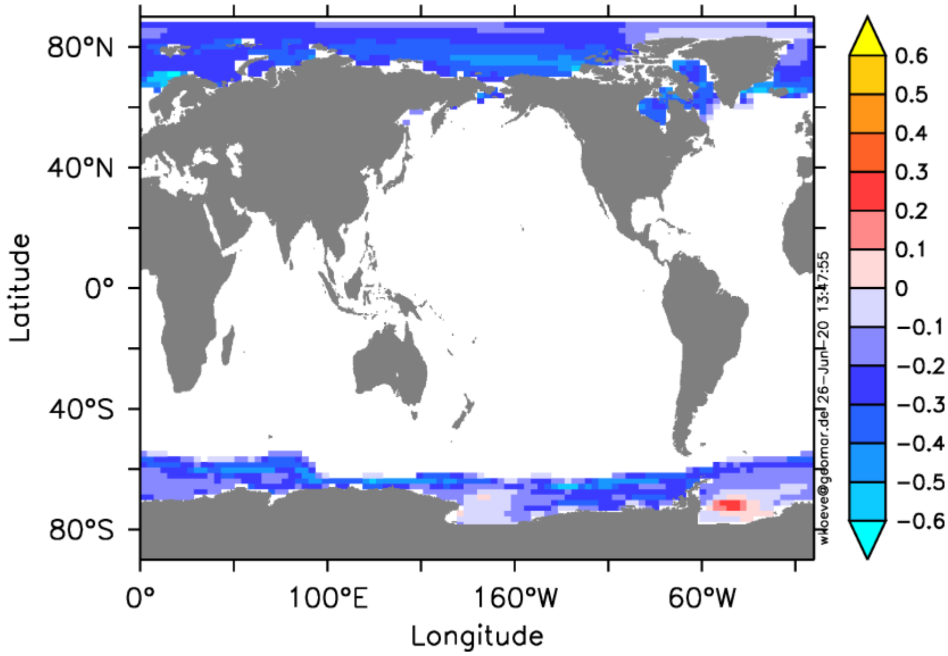


Figure S6. Change of ice cover (area fraction) between 1770 and 2100 in run COUPLED.

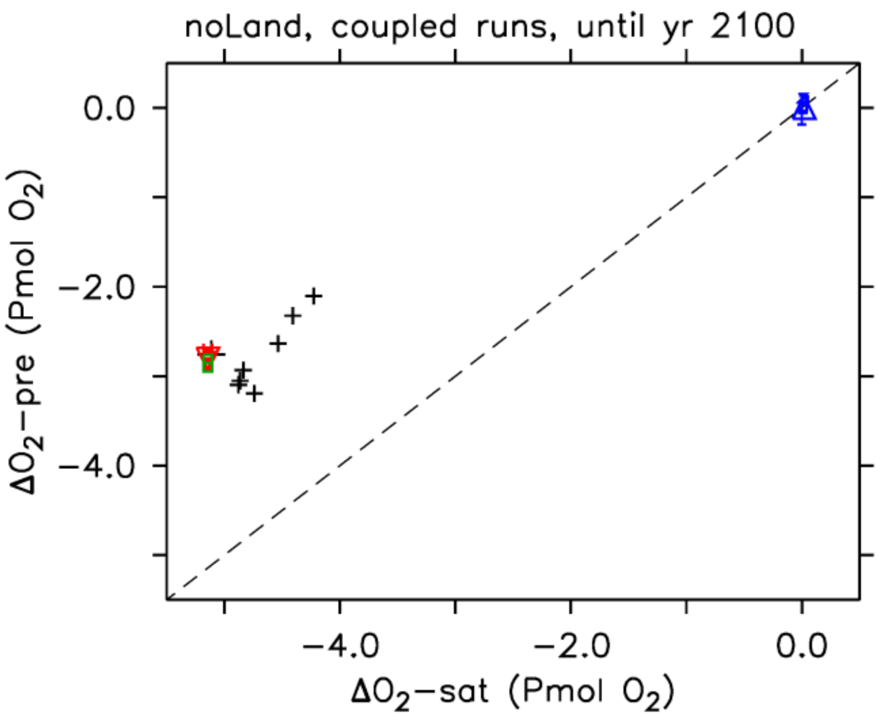


Figure S7. Transient change (2100 - 1770) of globally integrated preformed oxygen (O_2^{pre}) vs. globally integrated saturated oxygen (O_2^{sat}) from model runs 1a to 7a , 8-11, , and 12a-18a. For Details see caption of Fig. S5 and Tab. S1.

Table S1. Transient experiments carried out. We construct a range of potential responses of the biological carbon pump to climate change by combining four categories of experiments. (a) Coupled ocean-atmosphere runs (large black + in **Fig. 3**), in which changing biological rates as well as changing circulation affect oxygen and TOU tracer distribution according to the RCP85star climate scenario. (b) Coupled transient runs 2-6 with changing climate and circulation (like in COUPLED_SST) where biological rates from CTRL are assimilated at model run time everywhere or in specified regions (red symbols in **Fig. 3**). (c) Control runs 8-11 (no climate change and no circulation change) to which we assimilate biological rates from COUPLED at model run time everywhere or in specified regions (dark blue symbols in **Fig. 3**). (d) COUPLED model runs with modified background diffusivity (Kv, cm^2/sec) as indicated in column 3. SST difference to a respective control run is assimilated at model run time for the computation of oxygen solubility and gas-exchange. (See Supplementary Methods for details).

#	Symbols in Fig. 3	Run name	SST for ASE	Assimilation of biological rates
	-	COUPLED	-	-
	-	CTRL	-	-
1	large black +	COUPLED_SST	x	-
			x	-
2	red ∇	COUPLED_IMPOSE	x	x, everywhere
3	red 4	CoupAssS40	x	x, south of 40S
4	red 5	CoupAssS40N40	x	x, 40S to 40N
5	red 6	CoupAssN40	x	x, north of 40N
6	red 7	CoupAssS40no	x	x, north of 40S
7	green 8	CoupAss2x	x	x, everywhere, but twice
8	blue Δ	CTRL_IMPOSE	-	x, everywhere
9	blue 1	CtrlAssS40	-	x, south of 40S
10	blue 2	CtrlAssS40N40	-	x, 40S to 40N
11	blue 3	CtrlAssN40	-	x, north of 40N
12	small black +	Kv = 0.5	x	-
13	small black +	Kv = 0.4	x	-
14	small black +	Kv = 0.3	x	-
15	small black +	Kv = 0.2	x	-
16	small black +	Kv = 0.1	x	-
17	small black +	Kv = 0.05	x	-
18	small black +	Kv = 0.01	x	-

Table S2. Regional cumulative change in export production (EP) (z=130m) and the change in shallow TOU (z=130 to 1500m) between 1770 and 2100 (Pmol O_2).

Region	EP	TOU	TOU/EP
South of 40S	1.7	2.2	1.3
40S to 40N	-6.1	-1.0	0.16