Supplementary material for

A case for a pragmatic oxygen-based approach to quantifying the biological contribution to the marine carbon sink.

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SI Tables

Tab. S1. Preindustrial state estimates of Cremin. Elemental ratios used ($R_{C:P}$, $R_{C:O2}$) are those used in our model. See text and Online Methods for details.

Approach	**Global integral (Pg C equivalents)**
$AOU*R_{C:O2}$	1562
DIC^{remin} $	1290
$TOU*R_{C:O2}$ $	1272
$C^{soft} = (PO_4-PO_4^{pre})*R_{C:P}$ $	1303
tracer based $ (average)	1288+-16 (std)
$O_2^{dis,bio} * R_{C:O2}$	256
$C^{soft,\ tracer} + O_2^{dis,bio} * R_{C:O2}$	1544
$DIC^{dis,bio}$	520
$C^{soft,\ tracer} + DIC^{dis,bio}$	1808

$ estimates based on idealized model tracers DIC^{remin}, TOU, and PO_4^{pre}; the term ‘tracer based’ refers to the mean of the three tracer based estimates; see Online Methods for technical definitions and references.

SI Figures (captions)

Fig. S1: Comparison of the preindustrial state estimates of O_2-saturation (O_2^{sat}, mmol O_2 / m^3) and preformed O_2 (O_2^{pre}, mmol O_2 / m^3) of the default model variant. (a) Winter time surface O_2-saturation (%) showing undersaturation in high latitude waters. (b) Wintertime O_2 disequilibrium ($O_2^{dis} = O_2^{pre} - O_2^{sat}$, mmol O_2 / m^3). (c) O_2^{sat} section through the Atlantic (30°W, from North to South), the Southern Ocean (60°S), and the Pacific Ocean (140°W, from South to North), (d) like (c), but for preformed O_2 , (O_2^{pre}, mmol O_2 / m^3)

Fig. S2: Decomposition of the O_2 disequilibrium. (a) total O_2 disequilibrium (O_2^{dis}, mmol O_2 / m^3), (b) biotic component ($O_2^{dis,bio}$, mmol O_2 / m^3), and (c) physical component ($O_2^{dis,phys}$, mmol O_2 / m^3). See online methods for details on the methodology applied to decompose O_2^{dis}.

Fig. S3: Forcing, climate response and global marine response of the default model experiment (ZECmip1000). (a) CO_2-emissions forcing applied (Pg C / year), (b) change in atmospheric pCO_2 (ppm), (c) change in global mean surface air temperature (SAT, °C), (d) change in northern hemispheric (black) and southern hemispheric sea ice cover (1e6 km^2). (e) change in net primary production (NPP, Pg C / year). (f) change in export production (Pg C / year). Note: I still have to add the preindustrial values

Fig. S4: Sections through the Atlantic (30°W, from North to South), the Southern Ocean (60°S), and the Pacific Ocean (140°W, from South to North), showing the regional distribution of transient changes of AOU (a, b), TOU (c, d), sum TOU+$O_2^{dis,bio}$ (e,f), and $O_2^{dis,bio}$ (g, h), all in mmol O_2 / m^3. Panels a, c, e, g show differences between yr 100 and the initial state and panels b, d, f, h show differences between year 800 and the initial state. Warm colors indicate increase over time and cold colors decrease over time.

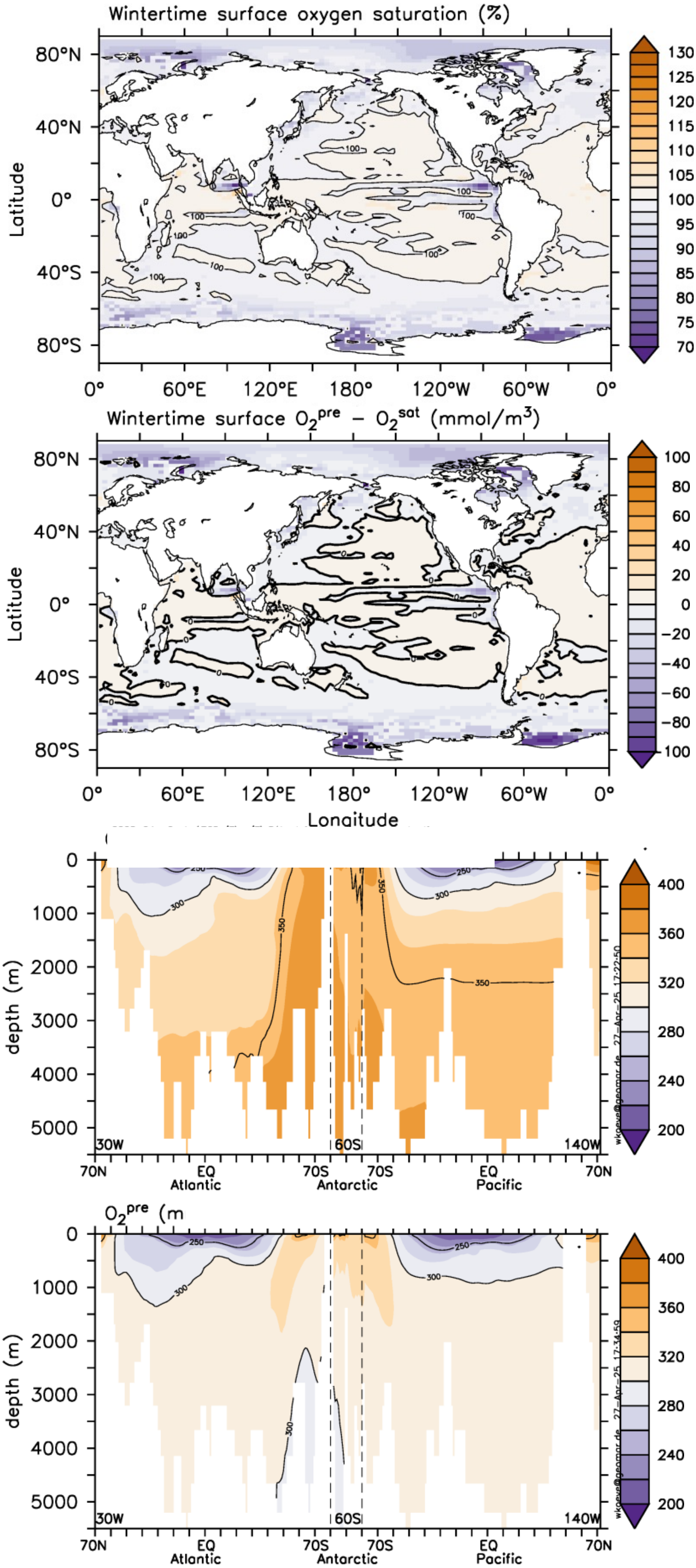
Fig. S5: Descriptive power of AOU during the climate change transient (default model variant), shown as ΔAOU /(ΔTOU+$\Delta O_2^{dis,bio}$)*100 (%). Solid line indicates the period with ΔAOU lower than -1 Pmol O_2, dashed line indicates period with ΔAOU between 0 and -1 Pmol O_2.

Fig. S6: Transient changes of surface air temperature (a, SAT, °C) and Atlantic meridional overturning (b, AMOC, Sv) from experiments taken from Koeve et al., 2024 and explored in Fig. 3c. In short, experiments have been forced with prescribed atmospheric pCO_2, initially increasing with 1% per year until reaching CO_2 doubling (all experiments). After reaching peak pCO_2 in year 70, experiments have been forced with decreasing atmospheric pCO_2 until reaching preindustrial pCO_2 again. Prescribed pCO_2 decreased with rates ranging from -1% per year (solid black lines) to -0.1% per year (light blue lines). See Koeve et al., 2024, SI for details.

Fig. S7: Three tracer based estimates of globally integrated ΔC^{remin} (BCP storage changes) from the default model variant using ZEC1000 forcing in fully coupled (COU*, solid lines) and biogeochemically-only coupled experiments (BGC*, dashed lines). TOU-tracer based estimate (black), DIC^{remin} tracer (red), and PO_4^{pre} (blue) based estimate. For details and equations see Online Methods.

Fig. S8: Forcing, climate response and global marine response of the biogeochemically only coupled model experiment (BGC*). (a) CO_2-emissions forcing applied (Pg C / year), (b) change in atmospheric pCO_2 (ppm), (c) change in global mean surface air temperature (SAT, °C), (d) change in northern hemispheric (black) and southern hemispheric sea ice cover (1e6 km^2). (e) change in net primary production (NPP, Pg C / year). (f) change in export production (Pg C / year).

Fig. S9: Comparison of computed O_2^{sat} (T,S) against explicit O_2^{sat} tracer. Section through the Atlantic (30°W, from North to South), the Southern Ocean (60°S), and the Pacific Ocean (140°W, from South to North) of (a) O_2^{sat}(T,S) - O_2^{sat}(tracer) and (b))O_2^{sat}(T,S) - O_2^{sat}(tracer)) / O_2^{sat}(tracer) *100



Wintertime surface oxygen saturation (%)
80°N
40°N
0°
40°S
80°S
Latitude
0°
60°E
120°E
180°
120°W
60°W
0°
130
125
120
115
110
105
100
95
90
85
80
75
70
Wintertime surface $O_2^{pre} - O_2^{sat}$ (mmol/m^3)
100
80
60
40
20
0
−20
−40
−60
−80
−100
Longitude
depth (m)
0
1000
2000
3000
4000
5000
30W
60S
140W
70N
EQ
Atlantic
70S
Antarctic
70S
EQ
Pacific
70N
400
360
320
280
240
200
250
300
350
O_2^{pre} (m

Fig. S1

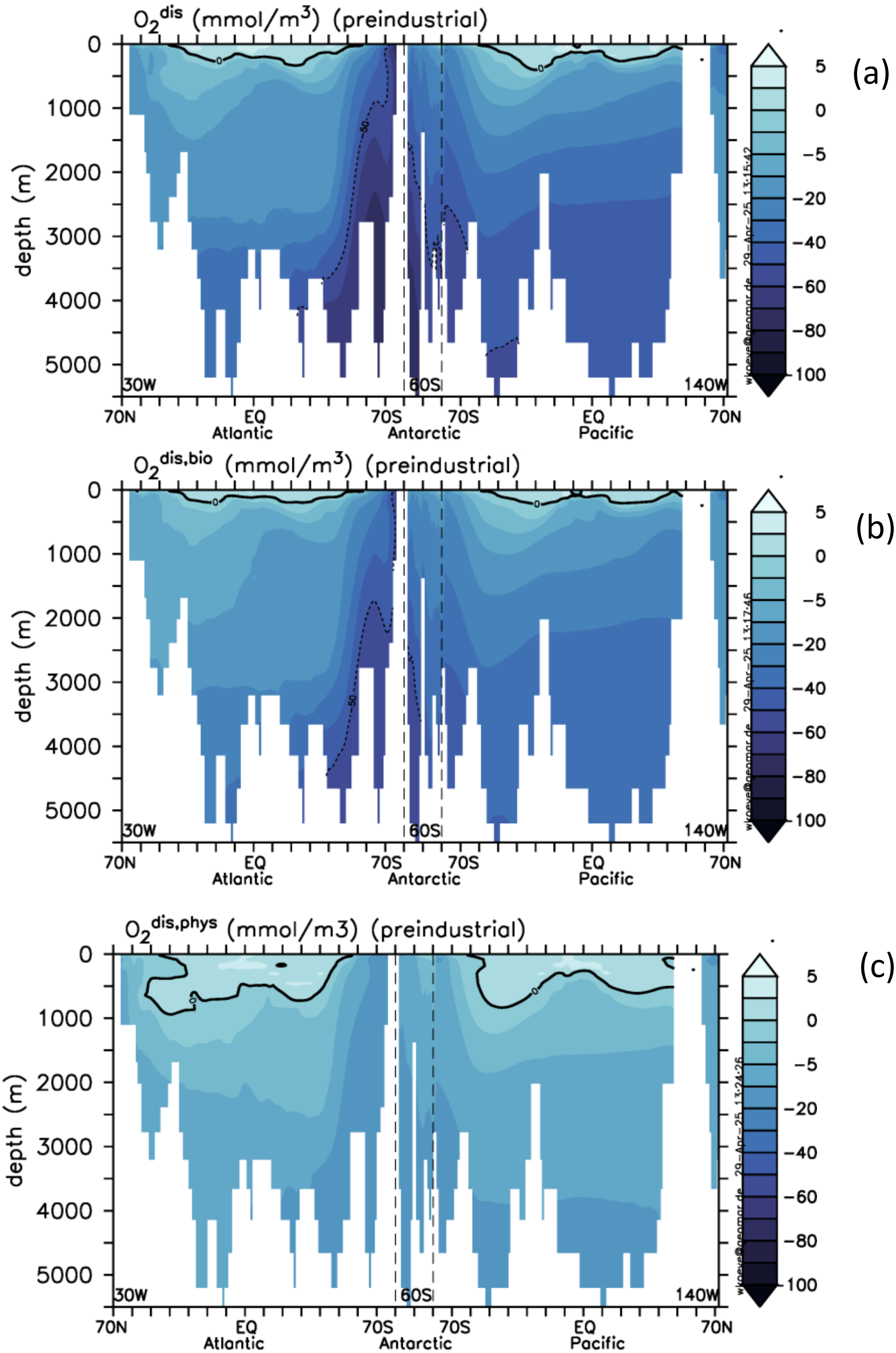
(a)

(b)

(c)

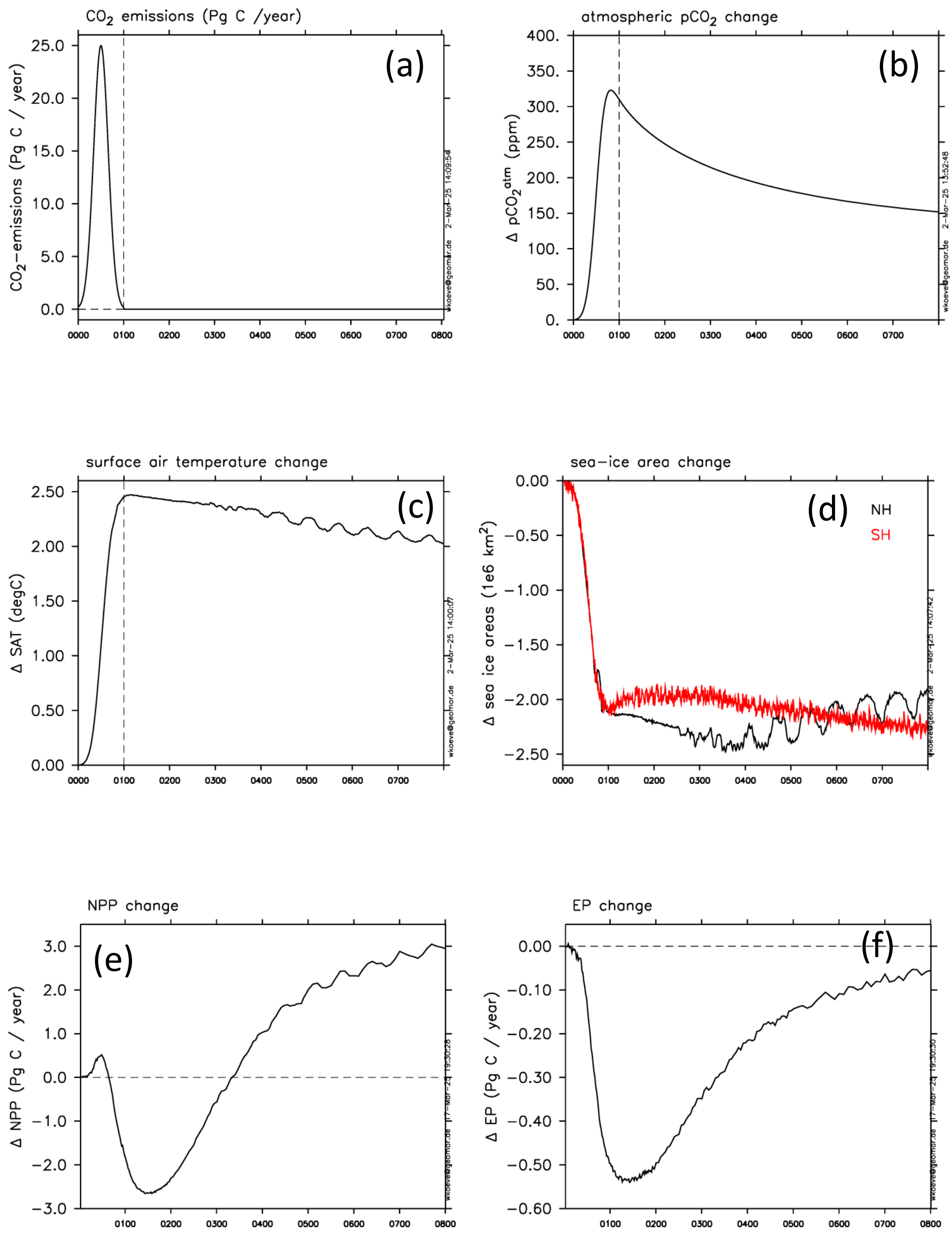
(d)

Fig. S2



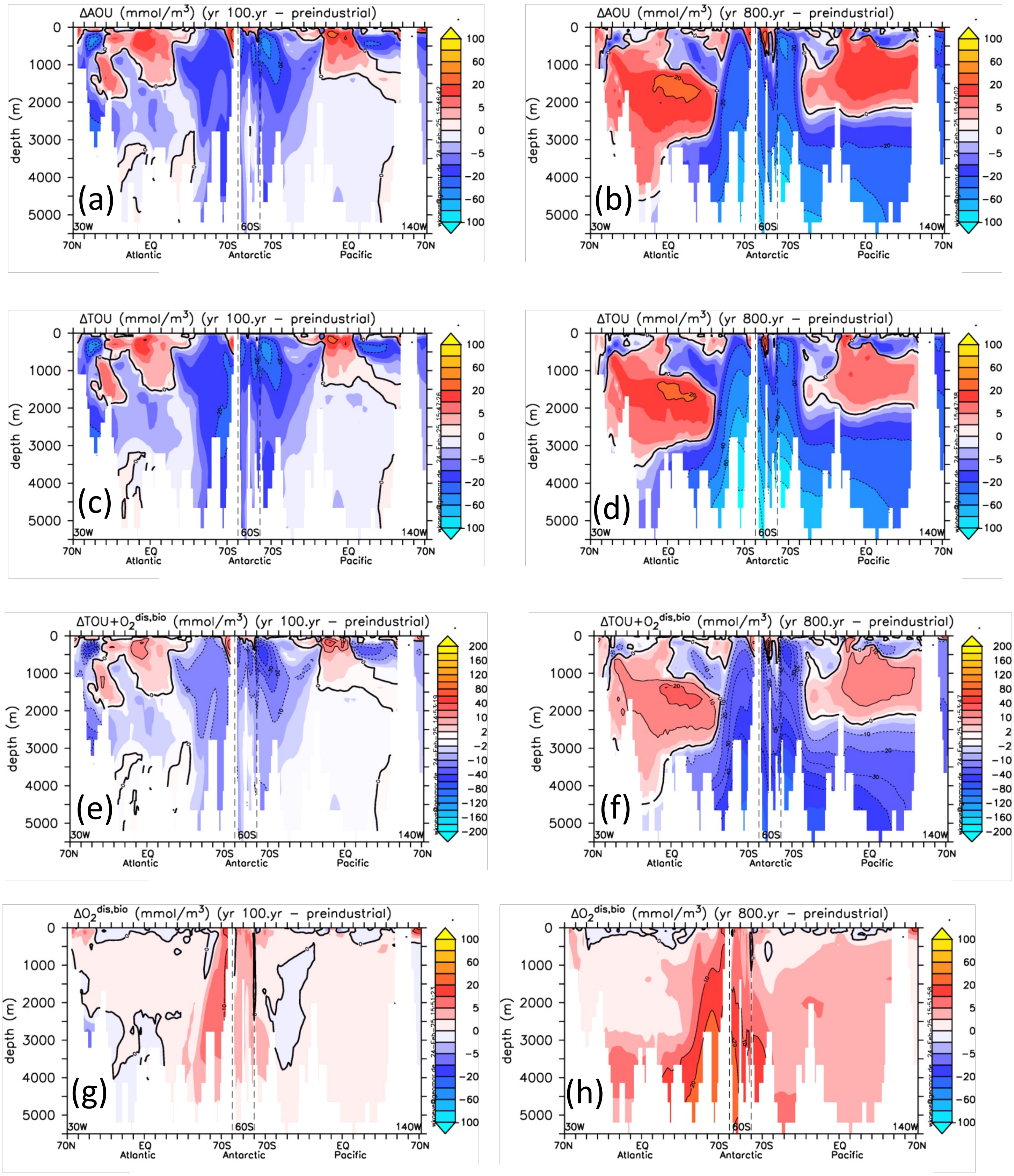
O_2^{dis} (mmol/m^3) (preindustrial)
(a)
$O_2^{dis,bio}$ (mmol/m^3) (preindustrial)
(b)
$O_2^{dis,phys}$ (mmol/m3) (preindustrial)
(c)
depth (m)
0
1000
2000
3000
4000
5000
30W
60S
140W
70N
EQ
Atlantic
70S
Antarctic
70S
EQ
Pacific
70N
-50
0
5
0
-5
-20
-40
-60
-80
-100

Fig. S3



CO_2 emissions (Pg C /year)
(a)
CO_2-emissions (Pg C / year)
25.0
20.0
15.0
10.0
5.0
0.0
0000 0100 0200 0300 0400 0500 0600 0700 0800
atmospheric pCO_2 change
(b)
Δ pCO_2^{atm} (ppm)
400.
350.
300.
250.
200.
150.
100.
50.
0.
0000 0100 0200 0300 0400 0500 0600 0700
surface air temperature change
(c)
Δ SAT (degC)
2.50
2.00
1.50
1.00
0.50
0.00
0000 0100 0200 0300 0400 0500 0600 0700
sea−ice area change
(d)
NH
SH
Δ sea ice areas (1e6 km^2)
0.00
−0.50
−1.00
−1.50
−2.00
−2.50
0000 0100 0200 0300 0400 0500 0600 0700
NPP change
(e)
Δ NPP (Pg C / year)
3.0
2.0
1.0
0.0
−1.0
−2.0
−3.0
0100 0200 0300 0400 0500 0600 0700 0800
EP change
(f)
Δ EP (Pg C / year)
0.00
−0.10
−0.20
−0.30
−0.40
−0.50
−0.60
0100 0200 0300 0400 0500 0600 0700 0800

Fig. S4



ΔAOU (mmol/m3) (yr 100.yr – preindustrial)
ΔAOU (mmol/m3) (yr 800.yr – preindustrial)
ΔTOU (mmol/m3) (yr 100.yr – preindustrial)
ΔTOU (mmol/m3) (yr 800.yr – preindustrial)
ΔTOU+O2dis,bio (mmol/m3) (yr 100.yr – preindustrial)
ΔTOU+O2dis,bio (mmol/m3) (yr 800.yr – preindustrial)
ΔO2dis,bio (mmol/m3) (yr 100.yr – preindustrial)
ΔO2dis,bio (mmol/m3) (yr 800.yr – preindustrial)
depth (m)
0
1000
2000
3000
4000
5000
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
30W
60S
140W
70N
EQ
Atlantic
70S
Antarctic
Pacific
100
60
20
5
0
–5
–20
–60
–100
200
160
120
80
40
10
2
–2
–10
–40
–80
–120
–160
–200

Fig. S5

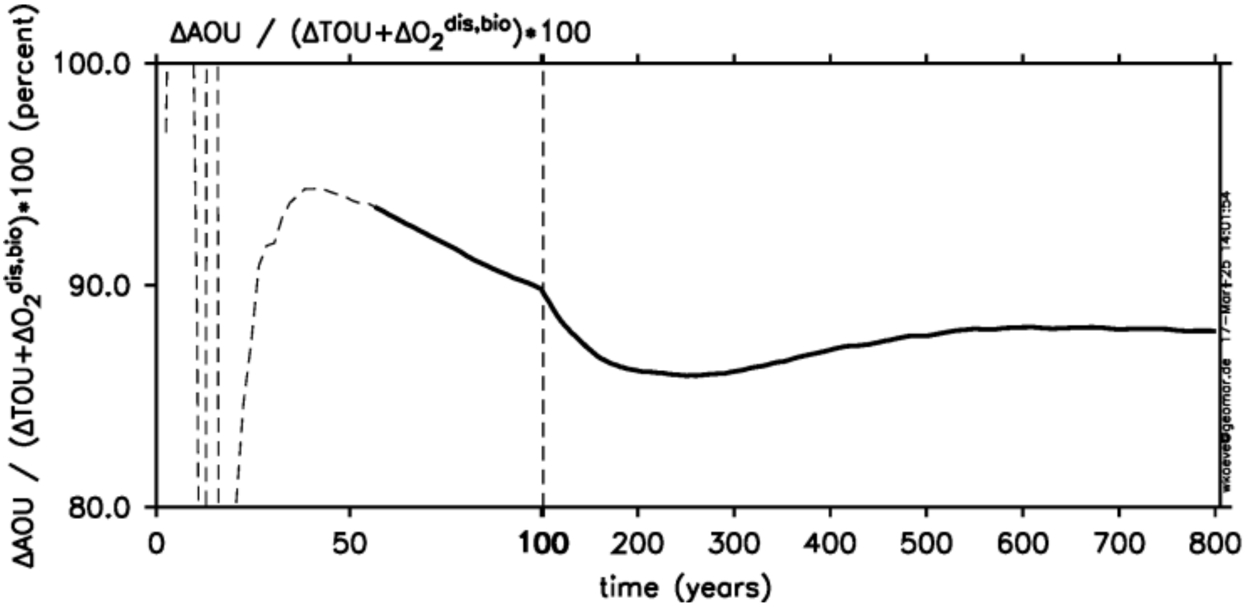

ΔAOU / (ΔTOU+ΔO2dis,bio)*100
ΔAOU / (ΔTOU+ΔO2dis,bio)*100 (percent)
100.0
90.0
80.0
0
50
100
200
300
400
500
600
700
800
time (years)

Fig. S6

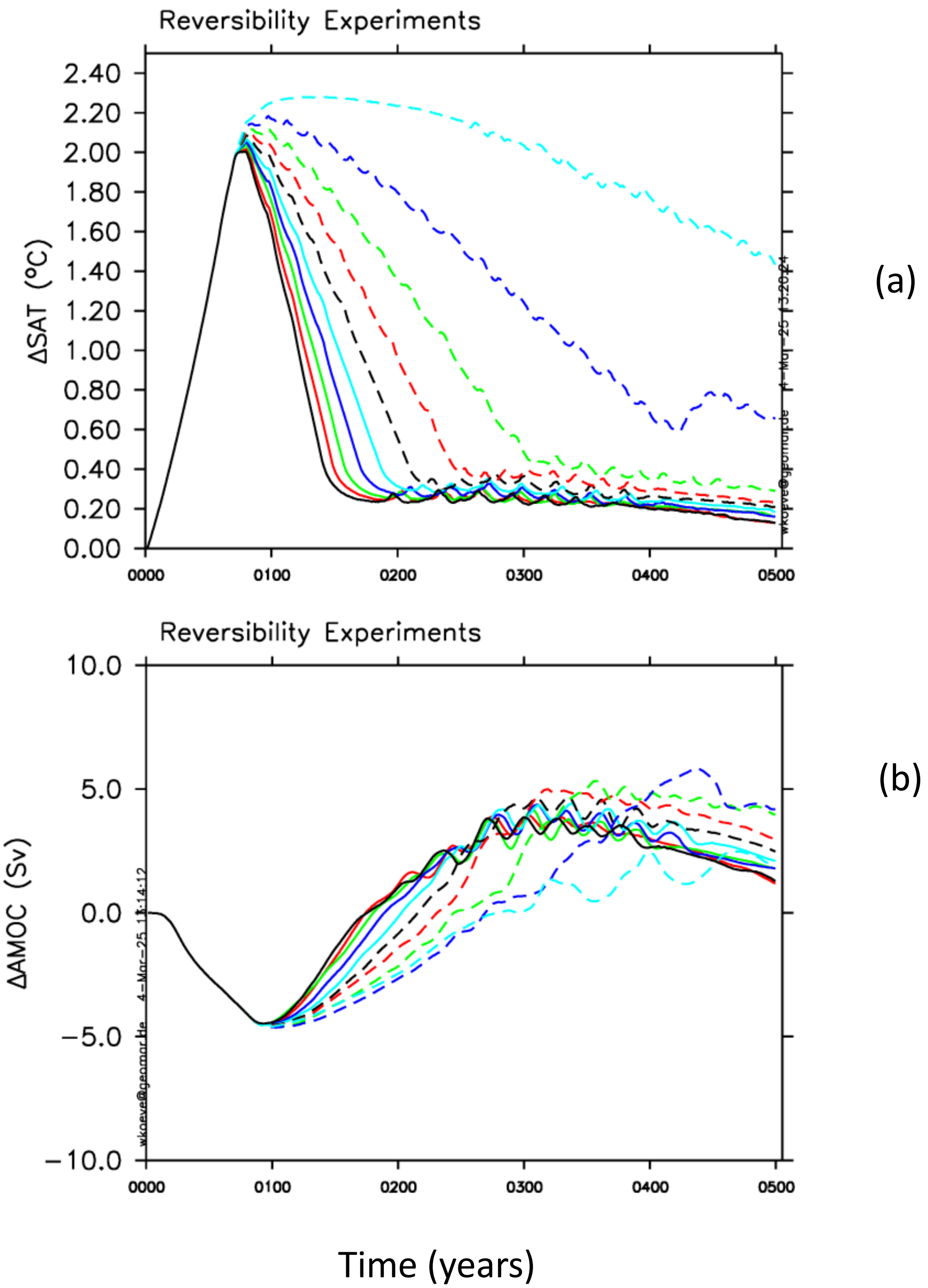

Reversibility Experiments
ΔSAT (°C)
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0000
0100
0200
0300
0400
0500
(a)
Reversibility Experiments
ΔAMOC (Sv)
10.0
5.0
0.0
−5.0
−10.0
0000
0100
0200
0300
0400
0500
(b)
Time (years)

Fig. S7

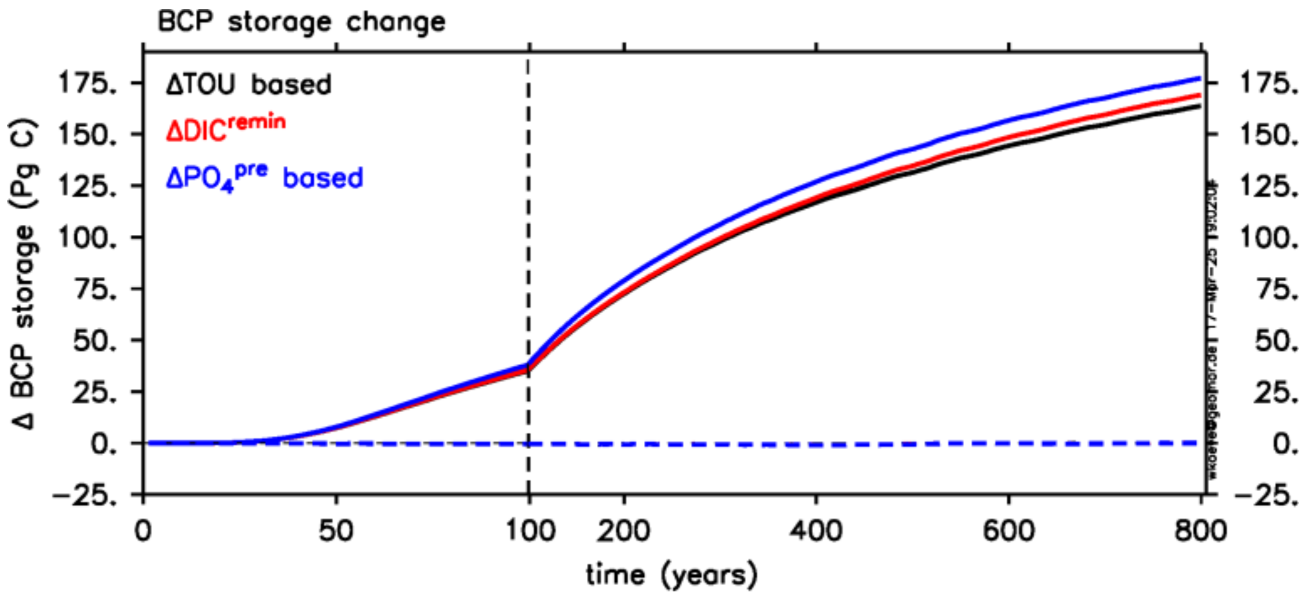
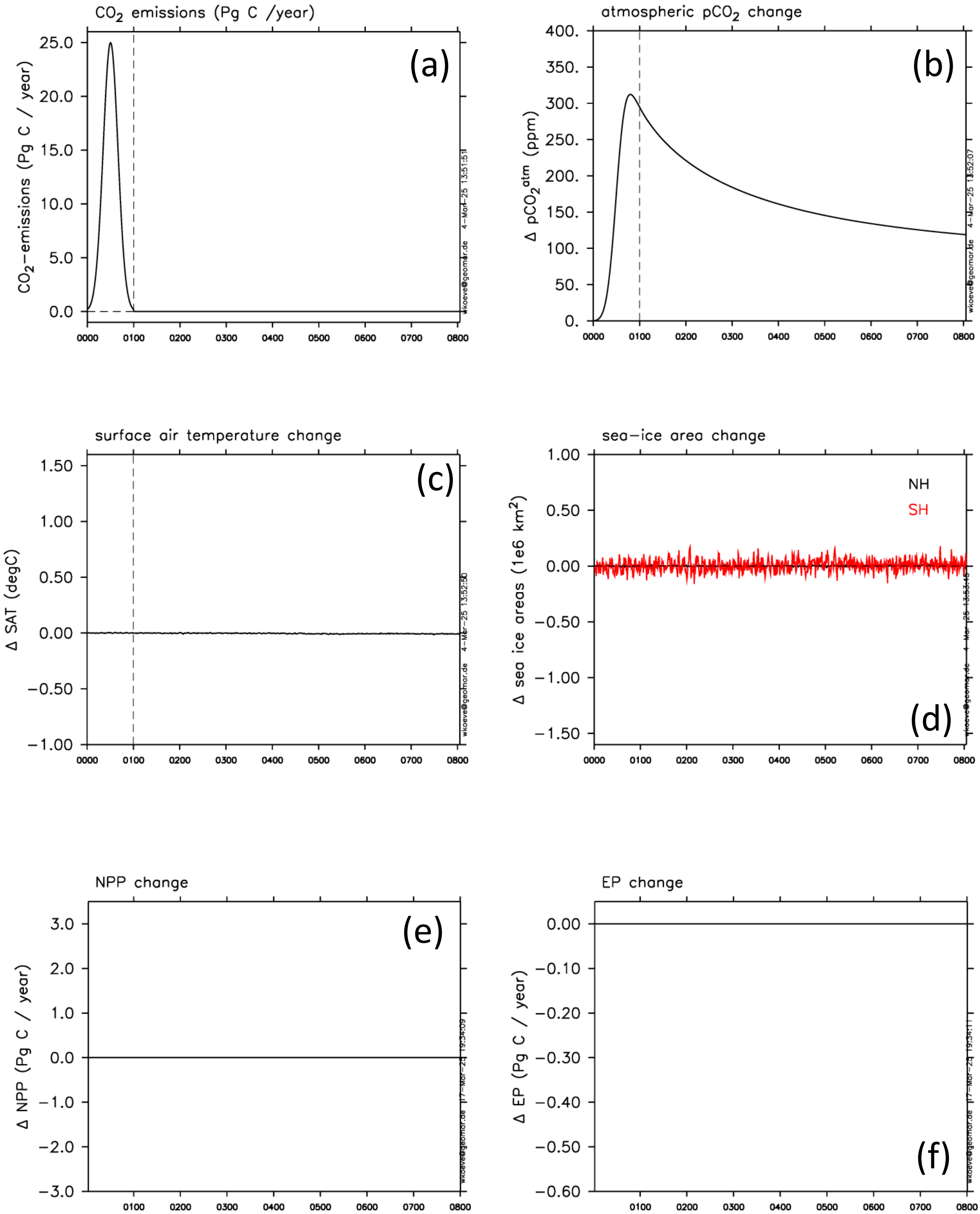
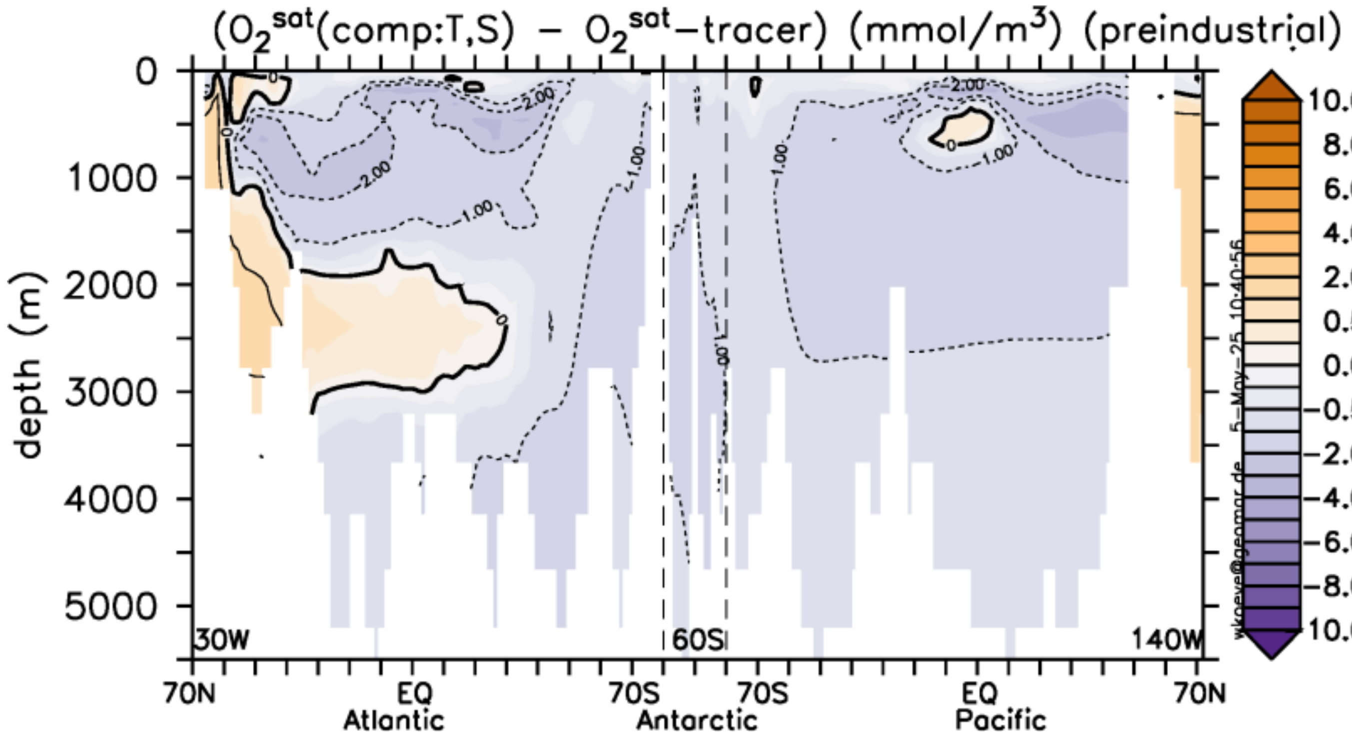

BCP storage change
ΔTOU based
ΔDIC^remin
ΔPO4^pre based
Δ BCP storage (Pg C)
time (years)
175.
150.
125.
100.
75.
50.
25.
0.
−25.
0
50
100
200
400
600
800

Fig. S8

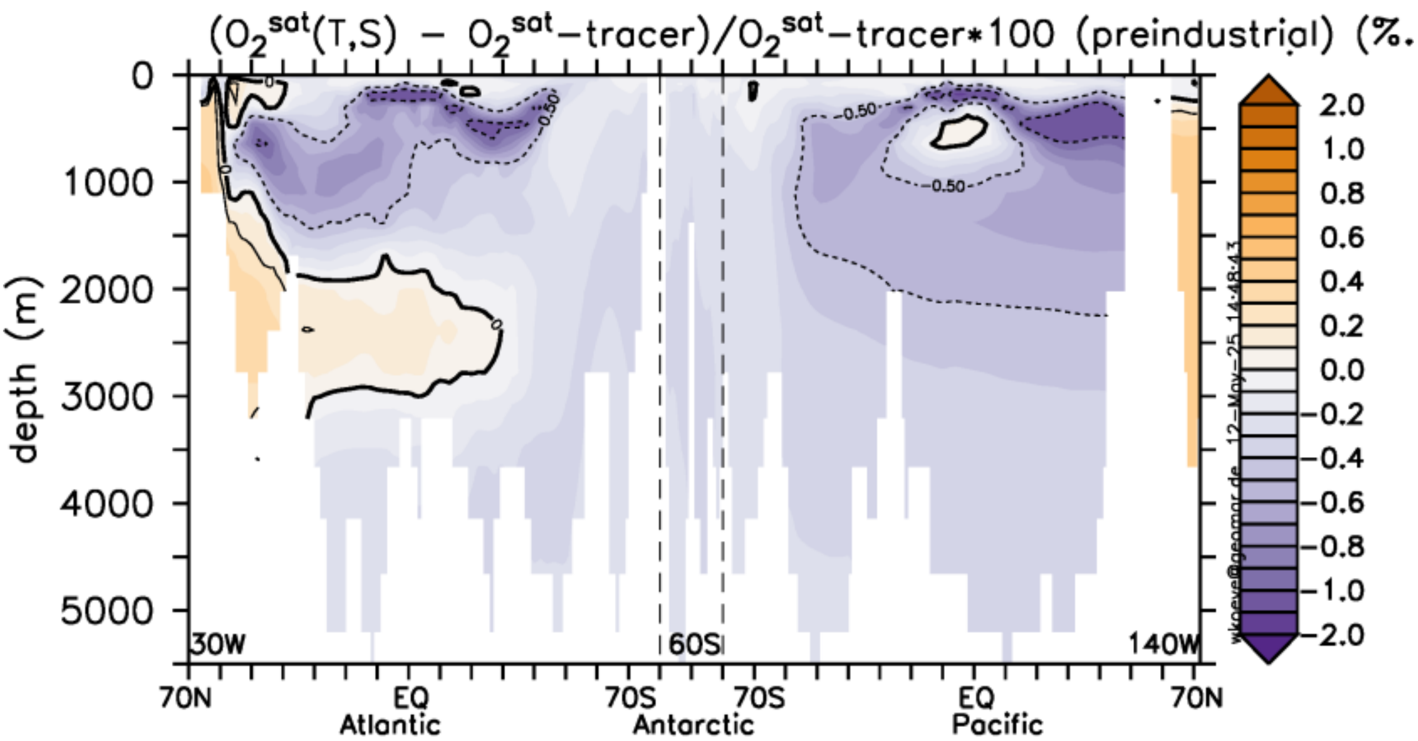


CO2 emissions (Pg C /year)
CO2−emissions (Pg C / year)
25.0
20.0
15.0
10.0
5.0
0.0
(a)
atmospheric pCO2 change
Δ pCO2atm (ppm)
400.
350.
300.
250.
200.
150.
100.
50.
0.
(b)
surface air temperature change
Δ SAT (degC)
1.50
1.00
0.50
0.00
−0.50
−1.00
(c)
sea−ice area change
Δ sea ice areas (1e6 km2)
1.00
0.50
0.00
−0.50
−1.00
−1.50
NH
SH
(d)
NPP change
Δ NPP (Pg C / year)
3.0
2.0
1.0
0.0
−1.0
−2.0
−3.0
(e)
EP change
Δ EP (Pg C / year)
0.00
−0.10
−0.20
−0.30
−0.40
−0.50
−0.60
(f)
0000
0100
0200
0300
0400
0500
0600
0700
0800

Fig. S9



$(O_2^{sat}(comp:T,S) - O_2^{sat}-tracer)$ (mmol/m^3) (preindustrial)
depth (m)
0
1000
2000
3000
4000
5000
30W
60S
140W
70N
EQ
Atlantic
70S
Antarctic
70S
EQ
Pacific
70N
10.0
8.0
6.0
4.0
2.0
0.5
0.0
-0.5
-2.0
-4.0
-6.0
-8.0
-10.0



$(O_2^{sat}(T,S) - O_2^{sat}-tracer)/O_2^{sat}-tracer*100$ (preindustrial) (%.
depth (m)
0
1000
2000
3000
4000
5000
30W
60S
140W
70N
EQ
Atlantic
70S
Antarctic
70S
EQ
Pacific
70N
2.0
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-2.0