Supplementary Information: The importance of Antarctic-Subantarctic surface mixing in establishing the biogeochemical divide

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In order to clarify the importance of the surface separation between the Antarctic and the Subantarctic regions on setting atmospheric carbon dioxide levels ($pCO_{2\ atm}$) and global export production we perform nutrient depletion experiments analogous to our GCM experiments in a simple six box model (Supplementary Fig. 1).

In our six box model (6BM) the Southern Ocean is represented by an Antarctic and a Subantarctic region. For simplicity, the lower (blue) circulation is represented entirely by mixing between the Antarctic surface waters (box a) and the deep ocean (box d), Mix_{ad}. The upper (red) circulation is represented by upwelling in the Subantarctic region (box s) and the subsequent transport of water to the low latitude thermocline (box l) and northern latitudes (box n). By analogy with the GCM study, alkalinity, temperature and salinity are assumed constant such that the 6BM is a soft-tissue only model. Biological production is parameterized like in the GCM, as nutrient restoring with a 30 day time scale.

The atmospheric pCO_2 impact of a change in surface nutrients depends on whether the change takes place in the Antarctic or Subantarctic boxes as well as on the strengths of circulation and mixing in the model. By analogy with the GCM experiments, we deplete separately the Antarctic box which is dominated by the lower circulation, and the Subantarctic box, whose properties are dominated by the upper circulation. Depleting nutrients in both the a and s boxes is equivalent to depleting nutrients south of 30^{o}S in the GCM.

We consider a standard version of the 6BM (model A) with no mixing between the Antarctic and Subantarctic boxes, such that the red and blue circulations are physically separated from each other at the surface. In a second version of the 6BM we apply 100 Sv of mixing between the Antarctic and Subantarctic boxes, Mix_{as}=100 Sv. Supplementary Figure 2 summarizes the circulation differences between these two models while Supplementary Figure 3 highlights results from depleting the Antarctic and Subantarctic boxes in the standard 6BM (top panels) and the high Antarctic-Subantarctic mixing 6BM (bottom panels).

If there is no mixing between the Antarctic and Subantarctic boxes, the relationship between atmospheric pCO_2 and export production is nonlinear and two branches, similar to the two branches in our GCM study, emerge on the production versus $pCO_{2\ atm}$ plots (compare Fig. 4 in the main text with Supplementary Fig. 3). The blue and red branches in Supplementary Figure 3 (panels 1a-1c) correspond to nutrient depletion of the Antarctic and Subantarctic boxes, respectively, while dotted lines show scenarios in which nutrients are partially depleted in both regions. Just like in the GCM, the Antarctic is more efficient at taking up atmospheric pCO_2 than the Subantarctic for a given local increase in biological production.

If mixing between the Antarctic and Subantarctic boxes is very large, the two boxes effectively act as a single box and the red and blue branches collapse into each other (Supplementary Fig. 3, panels 2a-2c). With effectively one Southern Ocean box, $pCO_{2\ atm}$ is now correlated in a simple linear fashion to both Southern Ocean production and production north of 30^{o}S, calculated in the 6BM as the sum between low latitude box and northern box export production.

With strong Antarctic-Subantarctic mixing the 6BM effectively reduces to a 5BM. The Subantarctic box becomes much more connected to the deep box than before such that Subantarctic nutrient depletion becomes much more efficient than before. Because of the large area of the s box compared to the a box, depleting nutrients in the Subantarctic box has a more sizable impact on atmospheric pCO_2 than the equivalent Antarctic depletion, and accounts for most of the 73 ppm atmospheric CO_2 drawdown following both a and s box depletion.

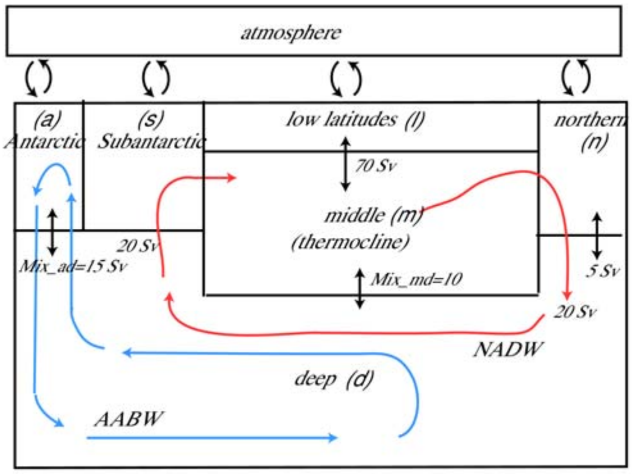
Supplementary Figure 3 shows that if mixing between the Antarctic and Subantarctic surface waters is small, the main points of our paper hold also in the simple box model:

(1) The efficiency of carbon sequestration is significantly higher in the Antarctic than in the Subantarctic, and

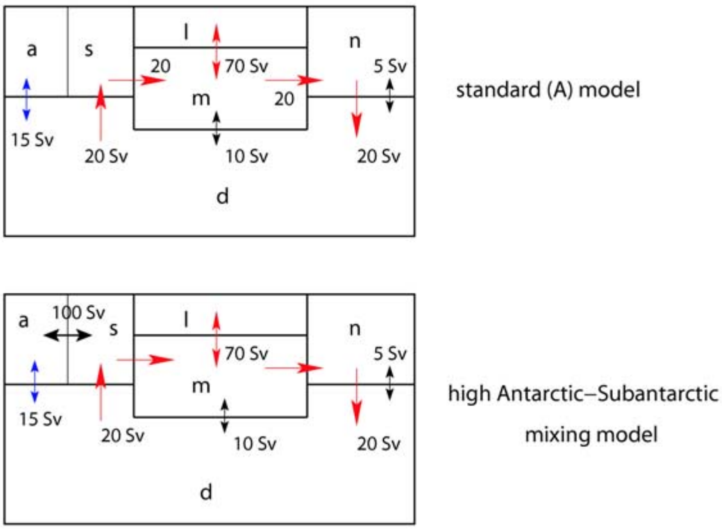
(2) Low-latitude biological production is driven primarily by nutrients in the Subantarctic rather than Antarctic waters.

The box model treats the deep ocean as a single box but still produces two biogeochemical regimes when the mixing between the surface Antarctic and Subantarctic box is small - not when the Antarctic-Subantarctic mixing is large. Therefore, the key parameter that determines whether the upper and lower circulations have fundamentally different biogeochemical expressions is the extent to which they can be separated in the surface layers (rather than within the deep ocean).

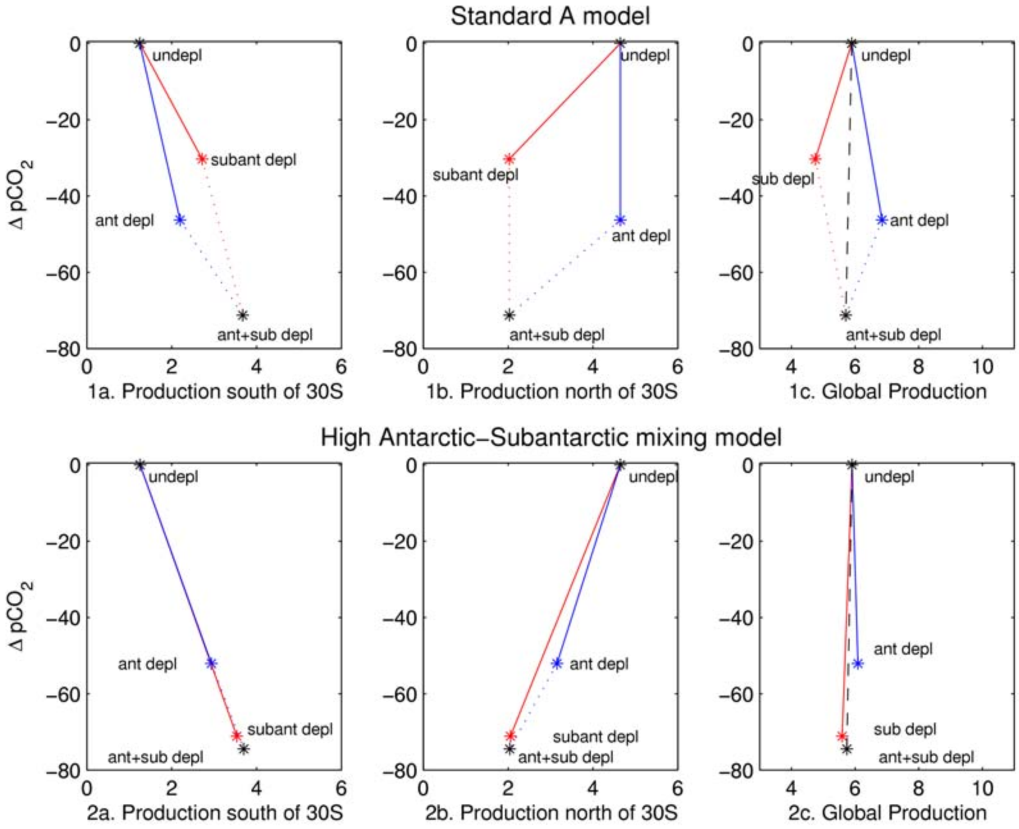
Finally, the presence of two well defined branches in the GCM (Fig. 3 in the main text) shows that in the GCM (and, we believe, in the real ocean) the upper and lower circulation regimes are well separated and the Antarctic- Subantarctic surface mixing is rather small.



Supplementary Figure 1: 6BM illustrating the separation of global oceanic circulation into a deep (blue) branch and an upper (red) branch. The areas of the Antarctic and Subantarctic are 5% and 17% of the total surface area, respectively. Model details shown in Supplementary Table 1.



Supplementary Figure 2: The standard six box model (A) and a high Antarctic-Subantarctic surface mixing model (bottom panel). Increasing Antarctic-Subantarctic surface mixing makes the lower (blue) and upper (red) circulations more interconnected.



Supplementary Figure 3: Change in atmospheric $p\mathrm{CO}_2$ (ppm) plotted against export production (GtC/yr) in two 6BMs after Antarctic (a) box, Subantarctic (s) box and Antarctic + Subantarctic nutrient depletions. The models used are the standard A model with no mixing between the and a and s boxes (panels 1a-1c) and a model identical with A except for 100 Sv mixing between the a and s boxes, Mix_{as}=100 Sv. Export production south of 30^{o}S is summed over the a and s boxes, production north of 30^{o}S is summed over the low and northern boxes. For the A model, the Antarctic is more efficient at taking up CO_2 than the Subantarctic, but the Subantarctic has a larger impact on global production, just like in the GCM. Compare panels 1a-1c with Figure 3 in the paper.

Supplementary Table 1: Input parameters for the six box model shown in Supplementary Figure 1

Fixed parameters	
Volume of the ocean	$1.345 \cdot 10^{18}$ m^3
Area of the ocean	$349 \cdot 10^{12}$ m^2
Temperature in all surface boxes	$10^{o}C$
Salinity in all surface boxes	34.7 psu
Alkalinity in all boxes	2370 µmol/kg
Initializing PO_4	2.17 µmol/kg
Initializing *DIC*	2280 µmol/kg
Depth of southern (a,s) boxes	250 m
Depth of low latitude (l) box	100 m
Depth of middle (m) box	400 m
Depth of northern (n) box	250 m
% area of Antarctic box	5
% area of Subantarctic box	17
% area of northern box	1
Conveyor transport	20 Sv
Mixing between l and m boxes, Mix_{lm}	70 Sv

Fixed parameters	
Total C:P in sinking particles $r_{C:P}$	106
% low latitude PO_4 ($PO_{4\,l}$) remineralized in m box	18
% $PO_{4\,l}$ remineralized in d box	82
gas exchange piston velocity	3 m/day
Surface PO_4 restored to - before depletion - after s box depletion	($PO_{4\,s}$* , $PO_{4\,l}$*, $PO_{4\,n}$*) (1.5, 0.4, 0.7) μmol/kg (0, 0.4, 0.7) μmol/kg
Nutrient restoring time scale	30 days
Variable Parameter	
Antarctic-Subantarctic mixing Mix_{as}	0 Sv or 100 Sv