Supplementary material: The relationship between atmospheric pCO$_2$, surface nutrients and globally averaged preformed PO$_4$

Here we confirm through a set of nutrient depletion experiments the existence of a robust and predictive functional relationship between globally averaged preformed PO$_4$ and atmospheric pCO$_2$ as shown in Fig 3c and described by Eq. (8) of the paper:

$$pCO_{2\,a} \simeq c_1 \cdot e^{-\frac{OCS_{soft}}{C_{buffered}}} = c_1 \cdot e^{\frac{r_{C:P}\cdot(\overline{PO_{4\,pref}}-\overline{PO_4})\cdot V_{oc}}{C_{buffered}}}$$

Fig S1 shows results of Southern Ocean nutrient depletion experiments, where we restore nutrients to zero everywhere at the ocean surface south of 30^{o}S. The total amount of PO$_4$ in the ocean is kept constant at all times. The total amount of inorganic carbon in the ocean-atmosphere system (total DIC in the ocean plus total CO$_2$ in the atmosphere) is kept constant at all times and identical between all models, while atmospheric pCO$_2$ is allowed to vary. The nutrient depletion experiments are carried out separately in all nine standard models (with biological time scale τ= 30days) described in Table 1 of the paper. Each model is run for more than 5000 years to a new equilibrium state while continuously restoring nutrients to zero.

Surface nutrient depletion (equivalent in our models to a strong increase in surface production) results in a strong decrease in surface nutrients and a decrease in the global preformed nutrient inventory, followed by a strong decrease in atmospheric pCO$_2$. The extent to which atmospheric pCO$_2$ decreases depends on the decrease in global preformed PO$_4$, which is a function of both surface PO$_4$ and the net deep ocean ventilation in the model.

We also performed global depletion simulations in our standard models (with biological time scale τ= 30days) by continuously restoring nutrients to zero everywhere at the ocean surface. In Fig S2 we compile equilibrium results from all our sets of simulations: standard (τ=30days) simulations, Southern ocean depletion simulations, global depletion simulations, as well as simulations with τ=1 year and τ=3 days.

Our paper shows through both theory and numerical models that globally averaged preformed PO$_4$ (or equivalently OCS_{soft}) cleanly predicts atmospheric pCO$_2$ in the limit of fast gas exchange. Figure S2d above confirms that, for all cases explored, there is a clean functional relationship between globally averaged preformed PO$_4$ and atmospheric pCO$_2$. This is the same exponential relationship shown in Fig. 3c of the main text and described by Eq. 8.

By contrast, figure S2a-c proves that there is no unique functional relationship between surface PO$_4$ and atmospheric pCO$_2$, regardless of how we define our surface PO$_4$ average. This is the case because global preformed PO$_4$ depends both on the preformed surface PO$_4$ in the deep water formation regions and on the change in the strength of AABW relative to NADW.

The "slope" of the pCO$_{2\,a}$ - surface PO$_4$ is not unique, and depends on how we define surface PO$_4$. Since deep water formation happens in convective centers south of 60^{o}S, surface PO$_4$ south of 60^{o}S is perhaps the most relevant surface end-member. However, points in Fig S2c appear clustered and surface PO$_4$ south of 60^{o}S is clearly not a robust predictor of atmospheric pCO$_2$.

To further illustrate the decoupling between the surface PO$_4$ and pCO$_{2\,a}$ we also note that it is possible for two different models to have widely different surface PO$_4$ values but identical atmospheric pCO$_2$ values. For example, the Southern Ocean surface PO$_4$ is lower by about 0.7 umol/kg in the nutrient-depleted windx2 model compared to the control LL model. However, the global preformed PO$_4$ is nearly identical in these two models, because the stronger deep ocean ventilation in the former model compensates for its lower surface preformed PO$_4$. As a consequence, atmospheric pCO$_2$ is nearly identical in these two cases.

Figure 1. Atmospheric pCO$_2$ (ppm) versus (a) surface PO$_4^{3-}$ averaged over the entire ocean (μmol/kg), (b) average surface PO$_4^{3-}$ south of 30^{o}S (μmol/kg), (c) globally averaged preformed PO$_4^{3-}$. Results shown for both control simulations (open symbols) and Southern Ocean surface nutrient depletion simulations (full symbols) in the nine models described in Table 1 of the paper with biological time scale τ=30 days. Fast gas exchange assumed. Circles denote lower Southern Ocean ventilation models, triangles higher ventilation models.

Figure 2. Atmospheric $p\mathrm{CO_2}$ (ppm) versus (a) surface $\mathrm{PO_4^{3-}}$ averaged over the entire ocean, (b) average surface $\mathrm{PO_4^{3-}}$ south of 30^oS, (c) average surface $\mathrm{PO_4^{3-}}$ between 60^oS and 80^oS, (d) globally averaged preformed $\mathrm{PO_4^{3-}}$. All $\mathrm{PO_4}$ values in units of μmol/kg. Results shown for control simulations (open circles and full black triangles), after Southern Ocean surface nutrient depletion (full blue triangles), or after global surface nutrient depletion (full red triangles) in the nine circulation models described in Table 1 of the paper. Fast gas exchange assumed. Globally integrated preformed $\mathrm{PO_4}$ is clearly the best indicator for atmospheric $p\mathrm{CO_2}$.