Supporting Information for "Effect of plankton composition shifts in the North Atlantic on atmospheric pCO_2"

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Introduction The supporting information contains a more elaborate explanation of the Simple Carbon Project Model v1.0 (SCP-M). Furthermore, it contains a figure of the model structure of the SCP-M and more results of the CESM2.

The Simple Carbon Project Model v1.0 In this study, we have used the Simple Carbon Project Model v1.0 (SCP-M) and the model description is based on earlier work (Boot et al., 2022). For a complete description we refer the reader to the original paper (C. M. O'Neill et al., 2019). The SCP-M is a carbon cycle box model with a focus on the carbon cycle in the ocean. Several tracers are resolved in the ocean among which dissolved inorganic carbon and alkalinity. In the ocean, circulation, air-sea gas exchange, biological production, calcium carbonate production and dissolution, river fluxes and sediment fluxes are resolved but mostly in a very parameterized way. Besides an oceanic part, there are also two terrestrial biosphere carbon stocks and anthropogenic emissions to the atmosphere.

The model consists of 10 boxes: 1 atmosphere box, 7 ocean boxes, and 2 boxes in the terrestrial biosphere (Fig. S1). There is no explicit sediment box in this model. This is a 2D box model with dimensions in the vertical and latitudinal direction, meaning that there is no dependence on longitude or ocean basins. Box 2 represents the northern high latitude box and therefore the North Atlantic.

Carbon and alkalinity in Box 2 are affected by the Atlantic Meridional Overturning Circulation (AMOC, ψ_2, orange arrow in Fig. S1), biological production (green arrow in Fig. S1), calcium carbonate production and dissolution (light gray arrow and wiggle in Fig. S1), and air-sea gas exchange (carbon only; dark gray arrow in Fig. S1). From these processes the AMOC, the biological and calcium carbonate production are constant in the model. Calcium carbonate dissolution is saturation dependent and therefore dependent on the pH of the ocean water. This pH is determined using a direct solver which uses the pH from the previous time step as a first estimate (Follows et al., 2006). To increase accuracy we run the solver twice each time step (note that in the original model the solver is run once). With the pH, oceanic pCO_2 can also be determined which is important for the air-sea gas exchange of CO_2, which is also dependent on the CO_2 concentration in the atmosphere. Temperature is affected by anthropogenic forcing, but this is prescribed and not dependent on atmospheric pCO_2; the salinity is constant.

For the purpose of studying the feedback processes we have made slight adaptations to the SCP-M. First of all, we have included biological fluxes that affect alkalinity following

$$A_{bio} = -\frac{16}{106} C_{bio} \tag{1}$$

Where A_{bio} is the biological alkalinity flux, C_{bio} the biological carbon flux, and the fraction $\frac{16}{106}$ represents the uptake of nitrate following constant stoichiometric ratios. Just as the biological DIC flux, it is constant. Secondly, we have updated the anthropogenic forcing to represent SSP5-8.5 instead of RCP8.5 (B. C. O'Neill et al., 2020; Green et al., 2021). And lastly, we have included the option for variable biological fluxes in the North Atlantic as a function of atmospheric pCO_2. This function is determined from fitting CESM2 biological fluxes to CESM2 atmospheric pCO_2 (Fig. 3c,d in the main text) and scaled to the original, constant fluxes in the SCP-M:

$$C_{bio,2} = \frac{pCO_2 * 0.0165 - 0.133}{pCO_{2,0} * 0.0165 - 0.133} \times -2.87 \times 10^{-10} \tag{2}$$

$$A_{bio,2} = \frac{-pCO_2 * 0.00616 + 0.0402}{|-pCO_{2,0} * 0.00616 + 0.0402|} \times \frac{16}{106} \times 2.87 \times 10^{-10} \tag{3}$$

To determine the feedback strength we choose initial conditions in the SCP-M for the year 2015 from CESM2 output for DIC and Alk averaged over the regions corresponding to the boxes. First, we determine the uncaptured dynamics in the SCP-M with respect to the CESM2 with regard to atmospheric pCO_2 for every time step. For this we use constant biological fluxes for all boxes in the SCP-M. Initial conditions for each timestep are adapted with a uncaptured dynamics parameter Y(t), following

$$pCO_2^{SCPM*}(t) = pCO_2^{SCPM}(t) + Y(t) \tag{4}$$

Where we determine Y(t) using a secant method, such that

$$pCO_2^{SCPM}(t+1) = pCO_2^{CESM}(t+1) \tag{5}$$

After determining the uncaptured dynamics, we can determine the feedback strength. To do this, we use the variable biological fluxes in the North Atlantic box as a function of atmospheric pCO_2 (Eq. 2 and 3). We then determine the feedback strength X(t) for each time step following a similar method:

$$pCO_2^{SCPM*}(t) = pCO_2^{SCPM}(t) + Y(t) + X(t) \tag{6}$$

Where we search for X(t), again using a secant method, such that

$$pCO_2^{SCPM}(t+1) = pCO_2^{CESM2}(t+1) \tag{7}$$

Note that if X(t) is negative, the feedback strength is positive, i.e. we have to lower our 'initial' atmospheric CO_2 concentration, because the ocean takes up less carbon causing more atmospheric pCO_2 to reside in the atmosphere.

References

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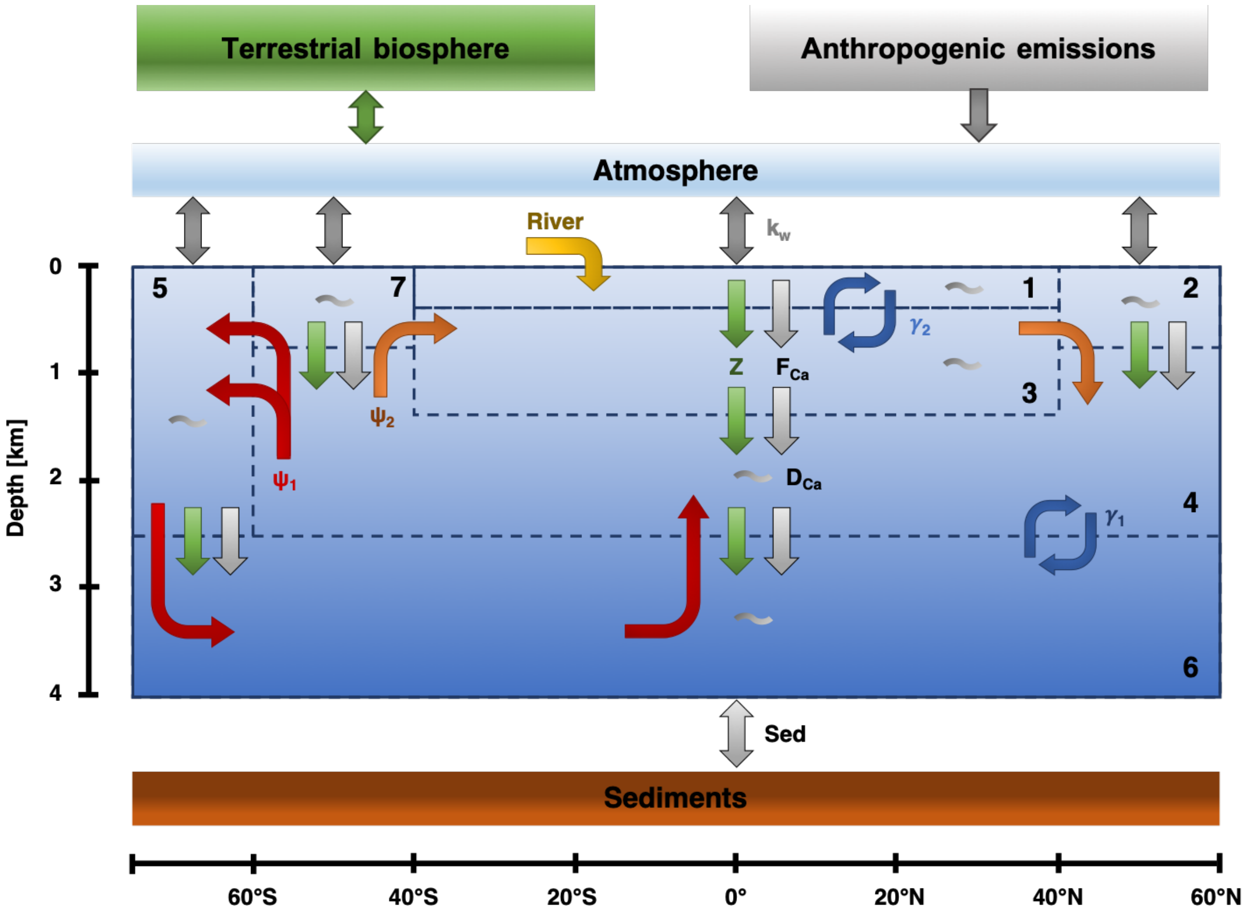

Figure S1. Box structure of the SCP-M. Box 2 represents the northern high latitude ocean. Figure adapted from (Boot et al., 2022).

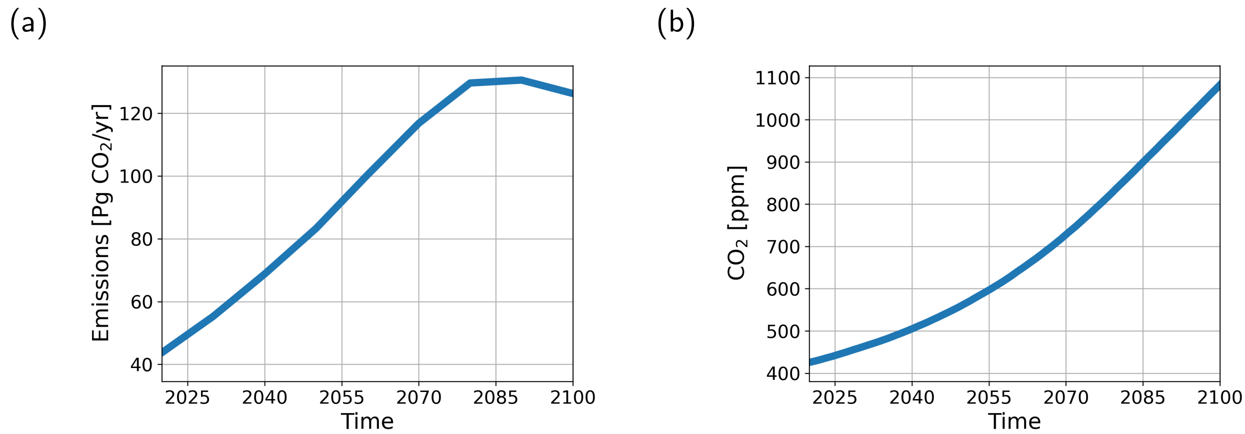

Figure S2. (a) Emissions of CO_2 in Pg CO_2 per year in the SSP5-8.5 scenario. (b) CO_2 concentrations in ppm as simulated in CESM2.

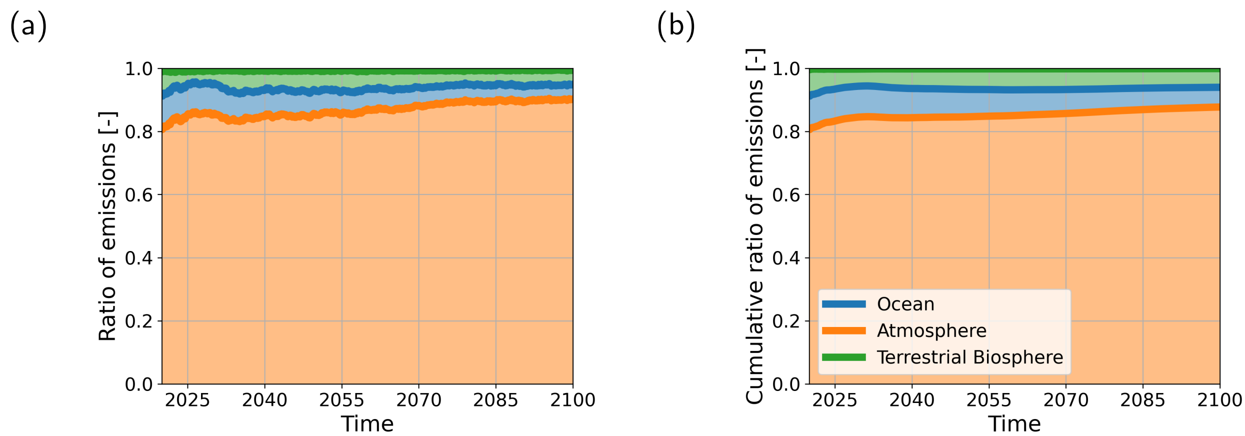

Figure S3. (a) Ratio of how the emitted CO_2 is distributed over the three different reservoirs atmosphere (orange), ocean (blue) and terrestrial biosphere (green) per time step in CESM2. (b) As in (a) but cumulative.

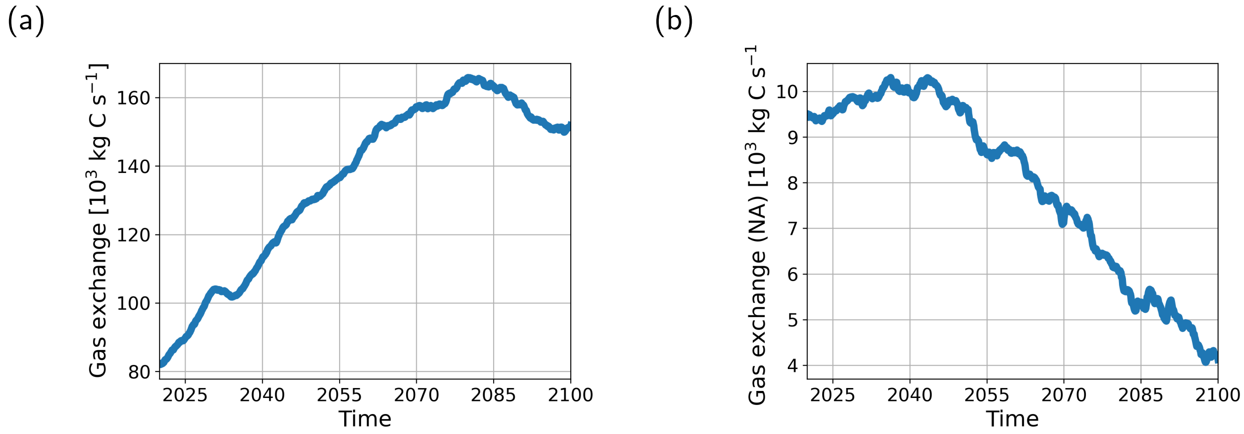

Figure S4. (a) Globally integrated air-sea gas exchange in 10^{-3} kg C s^{-1} in CESM2. (b) As in a, but integrated over the high latitude North Atlantic (45°-70°N × 270°-30°E).

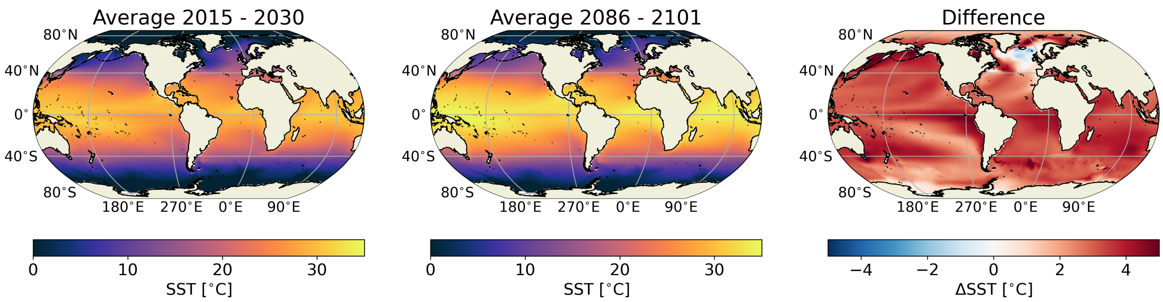

Figure S5. (a) Sea surface temperatures averaged over 2015-2030 in ° C in CESM2. (b) As in (a) but for the period 2086-2101. (c) The difference between the two. Red colors represent warming over the century, blue colors cooling.

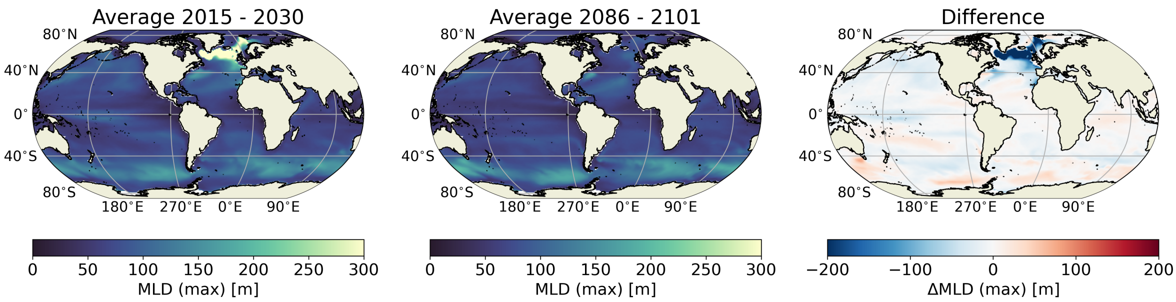

Figure S6. (a) Annual maximum mixed layer depth in m averaged over 2015-2030 in CESM2. (b) As in (a) but for the period 2086-2101. (c) The difference between the two. Red colors represent increasing depth over the century, blue colors decreasing depth.

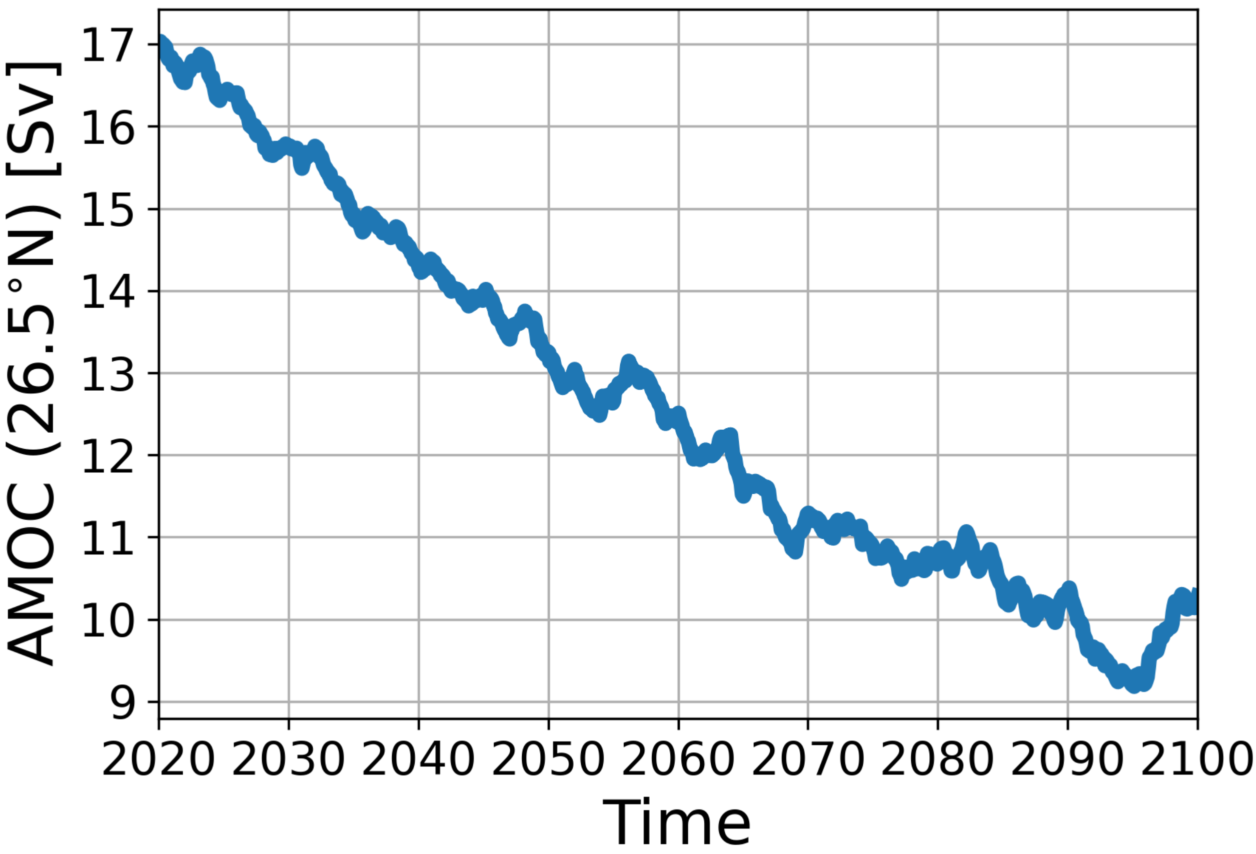

Figure S7. AMOC strength at 26.5°N in Sv as simulated in CESM2.

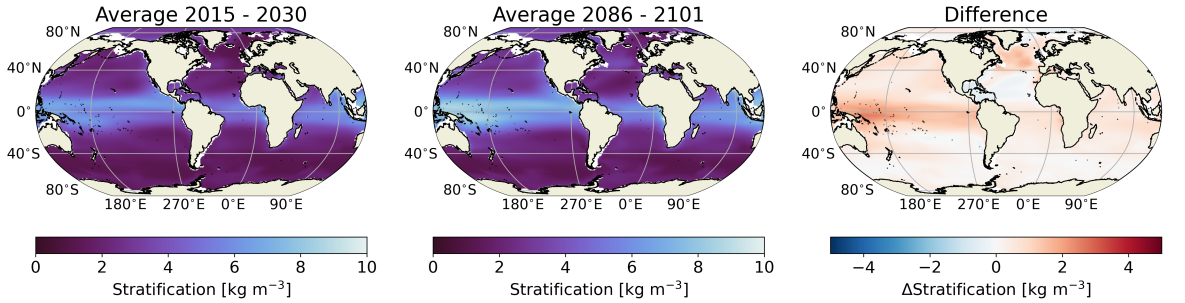

Figure S8. (a) Stratification in kg m^{-3} averaged over 2015-2030 in CESM2. Stratification is measured as the density difference between the surface and z=200 m. (b) As in (a) but for the period 2086-2101. (c) The difference between the two. Red colors represent increasing stratification over the century, blue colors decreasing stratification.

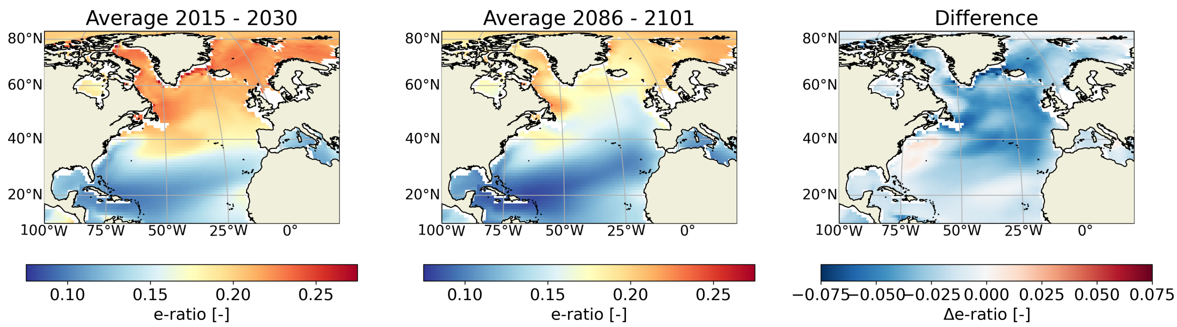

Figure S9. (a) Export production divided by Net Primary Production in the North Atlantic averaged over 2015-2030 in CESM2. (b) As in a but for the time period 2086-2101. (c) The difference between the two.

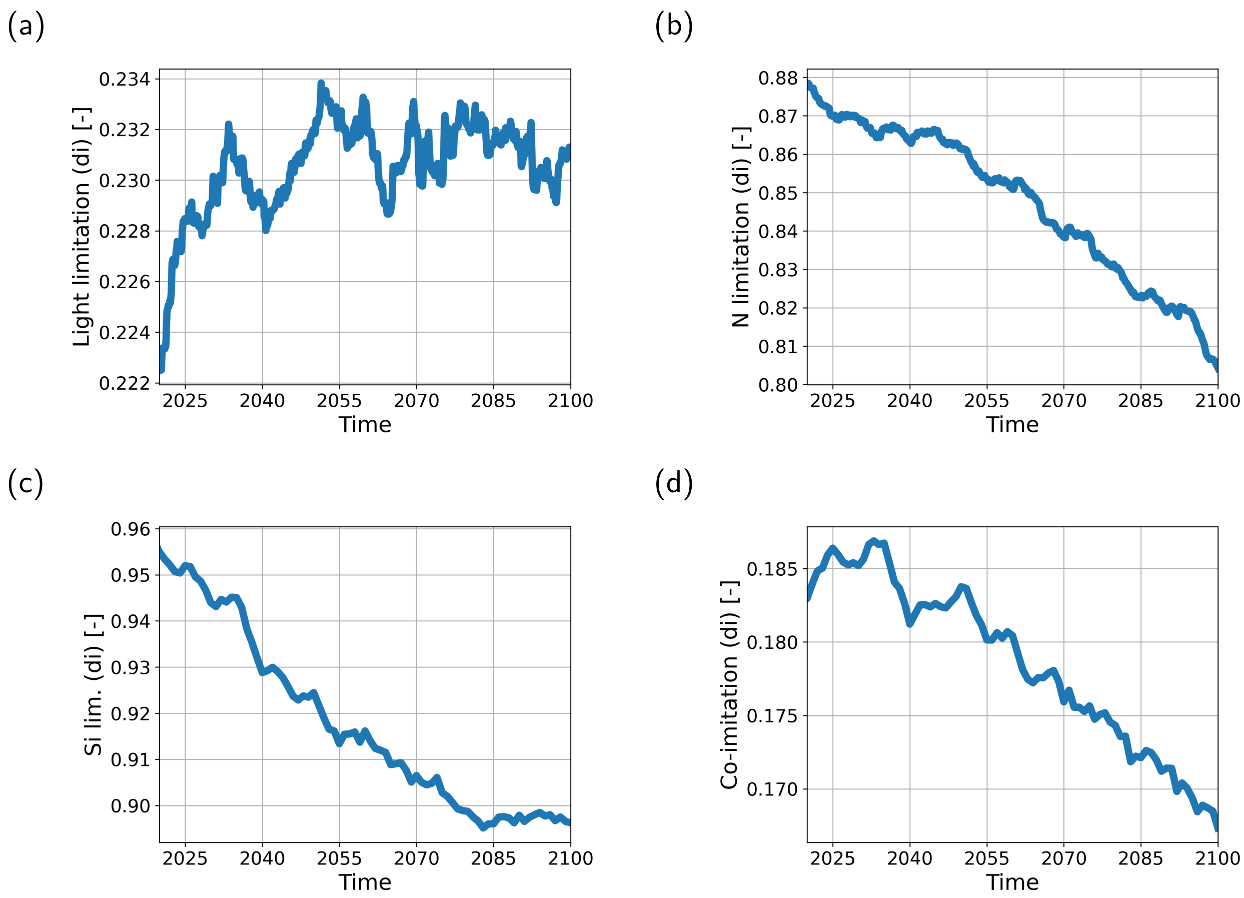

Figure S10. (a) Light limitation for diatoms in the region 45°-70°N × 270°-30°E in CESM2. Lower limitation values represent more limitation. (b) As in (a) but for nitrogen. (c) As in (a) but for silicate. (d) Nutrient-light co-limitation in the same region. Note that nitrogen is not necessarily the limiting nutrient in the entire domain for each time step. Different nutrient limitations are taken into account before averaging over mentioned region. Therefore the co-limitation is not simply the product of (a) and (b).

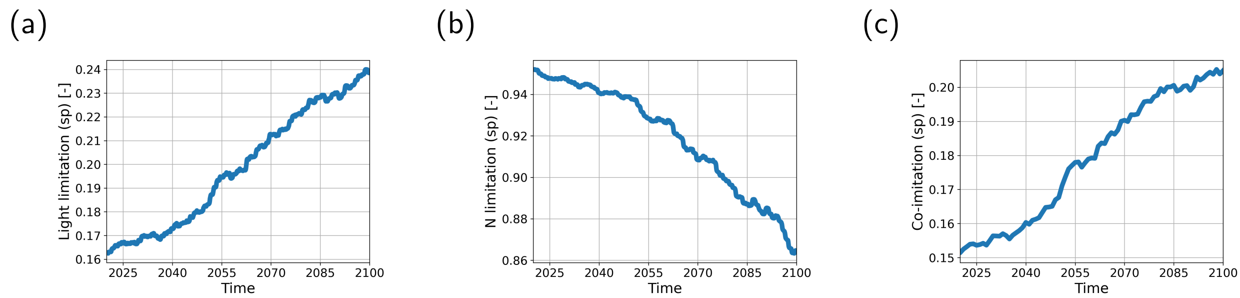

Figure S11. (a) Light limitation for small phytoplankton in the region 45°-70°N × 270°-30°E in CESM2. Lower limitation values represent more limitation. (b) As in (a) but for nitrogen. (c) Nutrient-light co-limitation in the same region. Different nutrient limitations are taken into account before averaging over mentioned region. Therefore the co-limitation is not simply the product of (a) and (b).

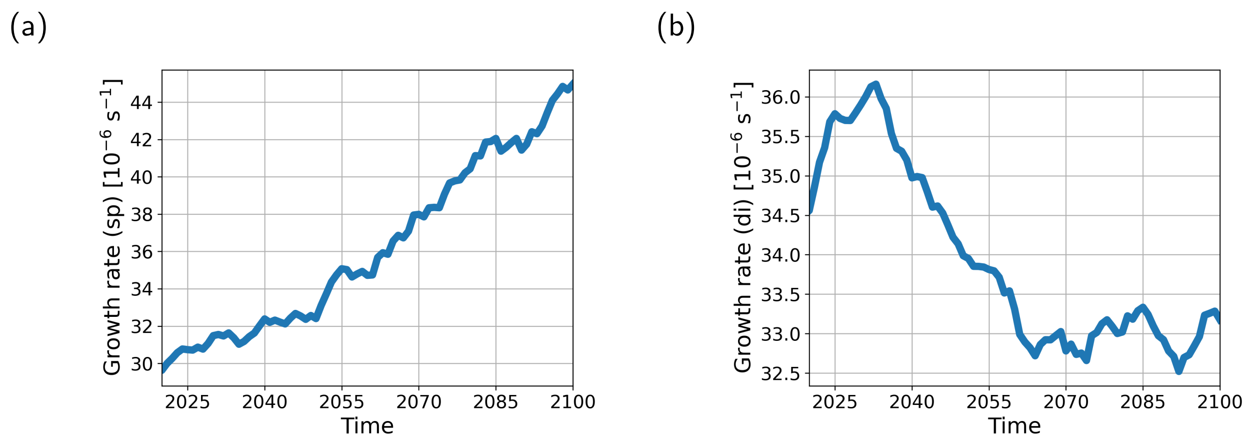

Figure S12. (a) Growth rate of small phytoplankton in 10^{-6} s^{-1} averaged over the top 100m in the region 45°-70°N × 270°-30°E in CESM2. (b) As in (a) but for diatoms.

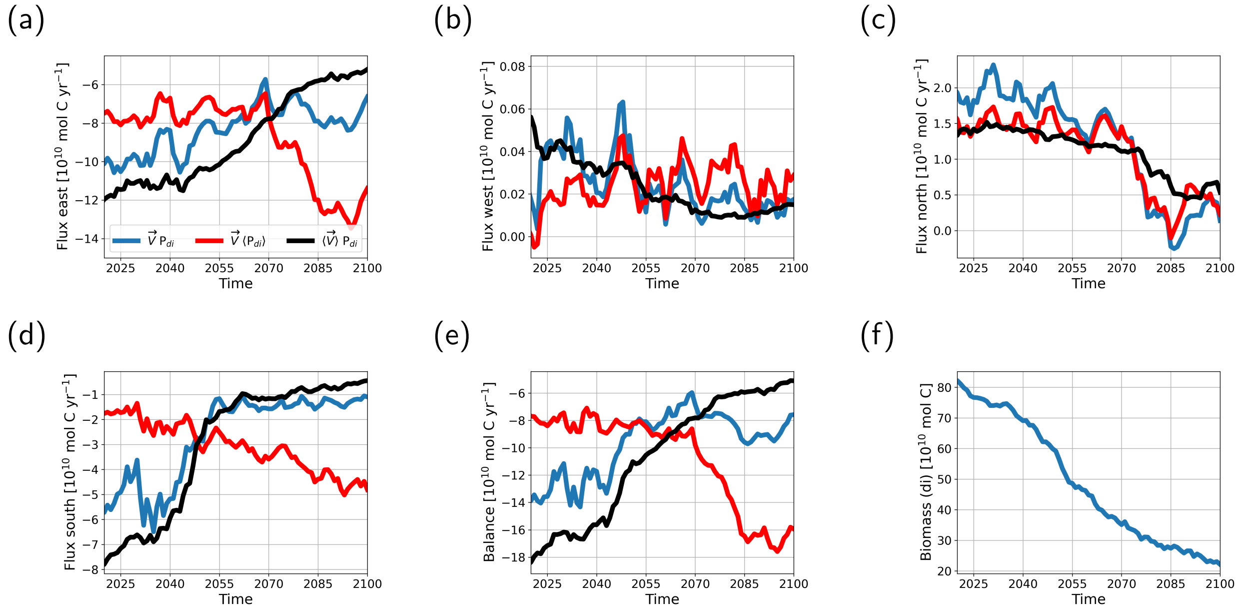

Figure S13. Advective fluxes of diatom biomass in and out of the region 45°-70°N × 270°-0°E for the top 150m of the water column for (a) the eastern boundary, (b) the western boundary, (c) the northern boundary, (d) the southern boundary, and (e) the sum of the four in CESM2. (a-d) In 10^{10} mol C yr^{-1}. (e) In 10^{10} mol C yr^{-1}. (f) The biomass content of this same region in 10^{10} mol C. Blue lines represent the actual calculated flux, red lines represent a flux where the biomass is time averaged over the entire period, and the black line a flux where the velocity field is time averaged over the entire period.

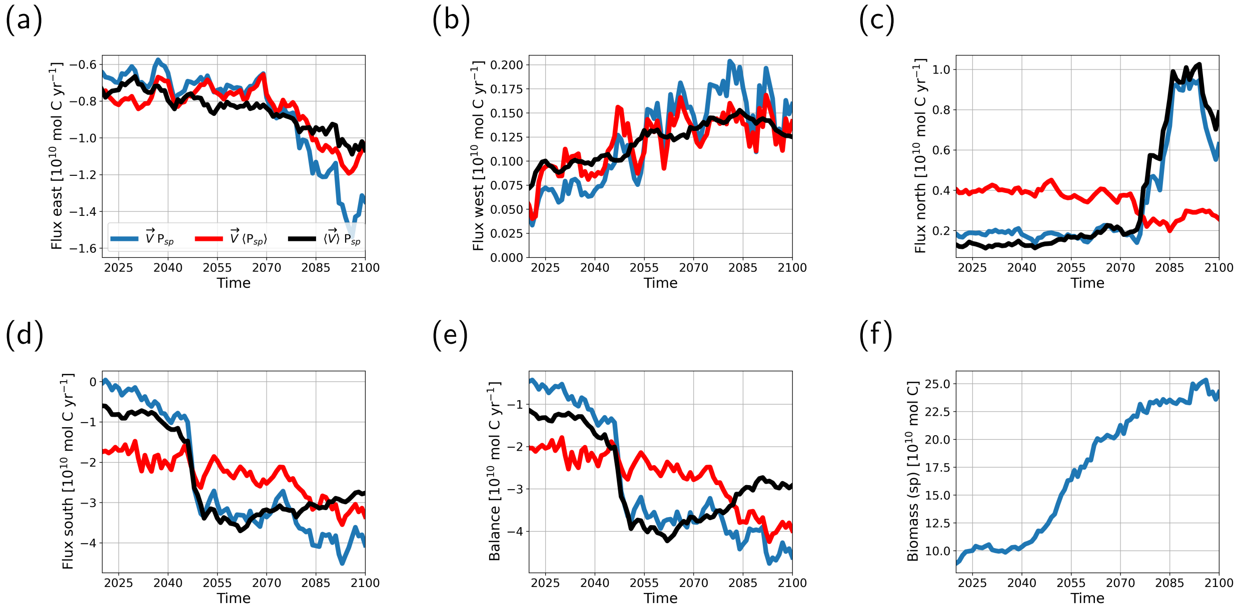

Figure S14. As in Fig. S13 but for small phytoplankton instead of diatoms.

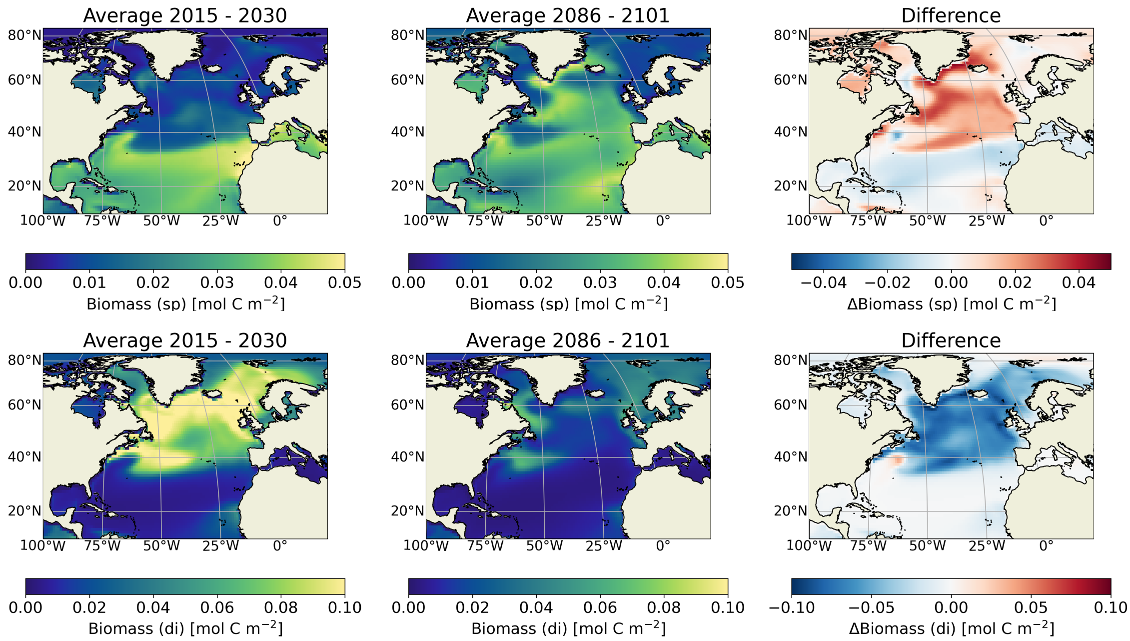

Figure S15. Phytoplankton biomass in mol C m^{-2} over the top 150 m for small phytoplankton (top row) and diatoms (bottom row) in CESM2. Note the different scaling for the diatoms. The left panels represent the average over 2015-2030, the middle panel the average over 2086-2101, and the right panel the difference between the two.