Long-term response of oceans to CO$_2$ removal from the atmosphere

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Supplementary Figure 1. Thermosteric sea level rise. Trajectories of steric sea level rise for RCP8.5 (black), CDR5 (red), CDR25 (orange), CDR5* (purple), CDR25* (blue), and RCP2.6 (green). The vertical green line marks the time when CDR25 reaches 280 ppm. Sea level rise with respect to the pre-industrial level in year 1800.
**Supplementary Figure 2. Change in ocean total carbon content.** Trajectories of steric sea level rise for RCP8.5 (black), CDR5 (red), CDR25 (orange), CDR5* (purple), CDR25* (blue), and RCP2.6 (green). The vertical green line marks the time when CDR25 reaches 280 ppm. All anomalies were calculated with respect to the pre-industrial content.
Supplementary Figure 3. Modeled pre-industrial states of zonally averaged values of pH, temperature and dissolved oxygen. (a) pH, (b) temperature (in °C), (c) dissolved oxygen concentrations (in µmol L⁻¹). These are the pre-industrial reference values for all calculated anomalies shown in this paper (year 1800), except for the anomalies in Supplementary Fig. 6 which refer to the unmitigated RCP8.5 scenario (CDR0).
Supplementary Figure 4. Depth-resolved evolution of zonally averaged change in pH, temperature and dissolved oxygen. Anomalies of pH (a, d, g), temperature (b, e, h) and dissolved oxygen (d, f, i), from 1800 to 2700. Top, middle, and bottom rows refer to CDR0, CDR5, and CDR25, respectively. Dashed lines show the shift in calcite compensation depth. All anomalies were calculated with respect to the pre-industrial state.
Supplementary Figure 5. Zonally averaged ocean tracer anomalies with respect to the baseline scenario RCP8.5 (CDR0) in year 2500. (a), (b), and (c) show the differences in pH, temperature and oxygen between CDR5 and CDR0, respectively, while (d), (e), and (f) show the same differences as in (a), (b), and (c) but between CDR25 and CDR0. Note that this is the only figure where anomalies were not calculated with respect to the pre-industrial state but with respect to CDR0 in 2500, to clearly show the CDR effect.
Supplementary Figure 6. Anomalies of atmospheric temperature, heat flux and CO₂-related radiative forcing, in CDR25. Shown are the anomalies with respect to 1800 of atmospheric surface temperature (red), radiative forcing of CO₂ (light brown; in W m⁻²) and ocean-to-atmosphere heat flux (orange; in W m⁻²) with positive values being heat transferred from the ocean to the atmosphere. Until approximately year 2400, the ocean absorbs heat from the atmosphere, later some of this heat is given back to the atmosphere.
phytoplankton

mixed layer depth

preindustrial

CDR 0

CDR 5

CDR 25
Supplementary Figure 7. Modeled pre-industrial values and latitude-resolved time evolution of the anomalies of surface phytoplankton concentration and mixed layer depth. The top row depicts the modeled pre-industrial states of phytoplankton concentration (in µmolC L⁻¹) and mixed layer depth (MLD, in m), the following rows depict the time evolution of latitude-resolved anomalies of surface phytoplankton concentration (in %) and MLD (in m), for CDR0, CDR5, and CDR25, respectively. Negative (positive) MLD anomalies represent a deepening (shoaling) of the mixed layer depth. All anomalies were calculated with respect to the pre-industrial state in year 1800, as depicted in (a) and (b).
Supplementary Figure 8. Correlations between surface anomalies of dissolved oxygen, phytoplankton concentration and pH in the Southern Ocean, in year 2500 under RCP8.5. Coloured symbols represent months during which light is available and photosynthesis can occur (October to February), black symbols represent dark months (March to September) without significant phytoplankton occurrence. (a) Correlation between dissolved oxygen anomalies (in µmol L⁻¹) and phytoplankton anomalies (in µmolC L⁻¹). (b) Correlation between dissolved oxygen (in µmol L⁻¹) and temperature (in °C). (c) Correlation between pH and phytoplankton (in µmolC L⁻¹), showing the extent to which increasing phytoplankton can counteract ocean acidification. Dissolved oxygen is significantly influenced by both temperature and photosynthesis, however, the effect of photosynthesis dominates and the correlation between temperature and oxygen is only visible in the dark months. Each point represents the anomaly ratios in a given month at each resolved location (grid cell) in the Southern Ocean. All anomalies were calculated with respect to the pre-industrial state in year 1800.
overturning streamfunction (Sv)

(a) Preindustrial depth (km)

(b) CDR0 depth (km)

(c) CDR5 depth (km)

(d) CDR25 depth (km)
Supplementary Figure 9. Global overturning streamfunction for the pre-industrial state and the state in 2500 resulting from the RCP8.5 scenario with and without CDR. (a) pre-industrial state (year 1800), (b), (c), and (d) state in 2500 for CDR0, CDR5, and CDR25, respectively. Red shading and positive values represent clockwise circulation, blue shading and negative values represent counterclockwise circulation.
Supplementary Figure 10. Zonally averaged pH anomalies for RCP2.6 and CDR25*/180ppm, in year 2410. (a) pH anomalies resulting from the RCP2.6 scenario. (b) pH anomalies resulting from CDR25* until the atmospheric CO$_2$ concentration reaches 180 ppm. Both sections show the state in year 2410, which is the time when the globally averaged pH anomalies of both scenarios reach the same value. Grey shaded areas show the ocean’s topography. All anomalies were calculated with respect to the pre-industrial state in year 1800.
Supplementary Figure 11. Zonally averaged pH anomalies for RCP2.6 and CDR25*/280ppm, in year 2530. (a) pH anomalies resulting from the RCP2.6 scenario. (b) pH anomalies resulting from the RCP8.5 scenario combined with CDR of 25 GtC yr-1 starting in 2150 until the atmospheric CO$_2$ concentration reaches 280 ppm. Both sections show the state in year 2530, which is the time when the globally averaged pH anomalies of both scenarios reach the same value. Grey shaded areas show the ocean’s topography. All anomalies calculated with respect to the pre-industrial state in year 1800.