Project: **1103**

Project title: **AWI-CM with carbon cycle**

Principal investigator: **Judith Hauck**

Report period: **2025-11-01 to 2026-10-31**

Summary

In the report period, project 1103 was used to (i) repeat SOFIA experiments with AWI-ESM-1-REcoM after corrections of its freshwater code (Sect. 1) and (ii) develop the carbon cycle model AWI-ESM-3-CC for CMIP7 and run its C-driven pre-industrial simulations (Sect. 3). AWI-ESM-1-REcoM output of this project was further used to study carbon–climate feedbacks in C- and E-driven overshoot scenarios (Sect. 2), ocean alkalinity enhancement (Nagwekar et al., 2026), marine carbon dioxide removal (Sathyanadh et al., 2026, preprint), the biological carbon pump (Hauck et al., in preparation), Southern Ocean pCO_2 biases (Bushinsky et al., 2026), ventilation and interannual variability of ocean carbon uptake (Danek and Hauck, 2026), Arctic marine heatwaves (Gou et al., in review) and Antarctic meltwater (Muilwijk et al., 2026; Pauling et al., 2026). The cmorization of AWI-ESM-1-REcoM output (all C-driven experiments done; thanks to M. Schupfner and F. Wachsmann) and its archival in the WDCC at DKRZ (first experiment complete as blueprint for the others; thanks to E. Hertwig) were continued (Danek et al., 2023).

1. Antarctic freshwater and the Southern Ocean carbon cycle (SOFIA)

AWI-ESM-1-REcoM contributes to the Southern Ocean Freshwater Input from Antarctica (SOFIA) initiative, which adds Antarctic meltwater to coupled models (Swart et al., 2023). Effects on ice-shelf mass loss and Antarctic sea ice were published by Muilwijk et al. (2026) and Pauling et al. (2026). During the multi-model analysis of the carbon cycle response (Jouet et al., in review), errors in the freshwater code of AWI-ESM-1-REcoM were found and corrected. The corrections shifted the Southern Ocean dissolved inorganic carbon (DIC) trends of both antwater and piControl by about 5 PgC per century, while the freshwater-induced DIC increase remained at about 7–8 PgC (Fig. 1). The pre-industrial (Jouet et al., in review), historical and future SOFIA simulations (Jouet et al., in preparation) therefore had to be repeated, which was not foreseen in the request for 2026.

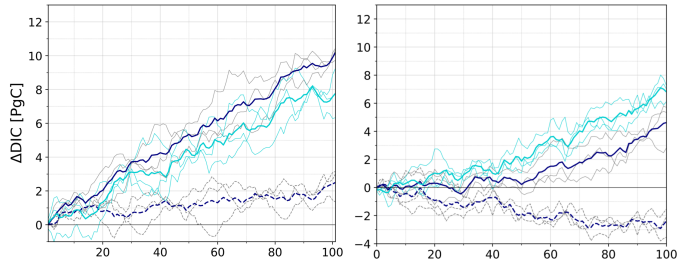


Fig. 1: Change in the Southern Ocean DIC inventory (PgC) since the start of the experiment before (left) and after (right) the code corrections: antwater (solid dark blue), piControl (dashed) and antwater minus piControl (cyan); thick: ensemble mean, thin: members.

2. C- and E-driven carbon–climate feedbacks under overshoot

Whether the carbon cycle responds differently to declining than to rising CO_2 is central for the effectiveness of net negative emissions. Studies found hysteresis, e.g. in Arctic Ocean acidification (Köhn et al., 2026) and in surface temperature and precipitation (Kim et al., 2022), and inconsistent carbon budgets in C- and E-driven historical simulations (Hajima et al., 2025). Carbon–climate feedbacks and their reversibility are, however, usually studied with idealized scenarios (Arora et al., 2020; Zickfeld et al., 2021; Chimuka and Zickfeld, 2026). Danek et al. (in preparation) analyze C- and E-driven AWI-ESM-1-REcoM simulations of the weak and strong overshoot scenarios SSP1-2.6 and SSP5-3.4-OS (O'Neill et al., 2016; Fig. 2). Global ocean CO_2 uptake follows a different path after than before the peak in atmospheric CO_2, a large hysteresis (Fig. 2, left), while its relation to the air–sea pCO_2 difference is nearly the same in all simulations (Fig. 2, right). In the E-driven runs, atmospheric CO_2 in 2100 is 18 (SSP1-2.6) and 42 ppm (SSP5-3.4-OS) lower than in the C-driven runs, which shifts the hysteresis to lower CO_2 and reduces the cumulative ocean uptake since 1850 by 15 –30 PgC. Depending on the setup, the global ocean becomes a carbon source by the end of the 21st century.

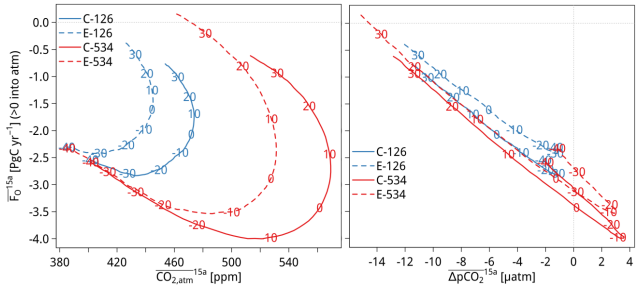


Fig. 2: C- (solid) and E-driven (dashed) air–sea CO_2 flux versus atm. CO_2 (left) and air–sea pCO_2 difference (right) for weak (blue) and strong (red) overshoot. Numbers mark years before (negative) and after (positive) peak atm. CO_2.

3. AWI-ESM-3-CC for CMIP7

AWI-ESM-3-CC (Streffing et al., in preparation) couples OpenIFS 48r1, FESOM 2.8 with the ocean biogeochemistry model REcoM 3 and the dynamic vegetation model LPJ-GUESS 4.1, with atmospheric CO_2 as a three-dimensional tracer, for C- and E-driven CMIP7 simulations. Compared with the request for 2026 (FESOM 2.6 on the CORE2 mesh, 126858 surface nodes), FESOM 2.8 now runs on the CORE3 mesh (220509 surface nodes) with ice-shelf cavities, important for dense water formation and carbon sequestration on the Antarctic shelves (Nissen et al., 2022), and interactive icebergs (Ackermann et al., 2024). Model development and the C-driven pre-industrial simulations were conducted with the

Levante project CAP7 (project 1469). The development delayed the CMIP7 experiments: the final C-driven spin-up is still running, and the remaining simulations of the 2026 plan are requested again for 2027. Some simulations used resources of other projects to avoid very long queue times in ba1103. The C-driven piControl carbon budget (Fig. 3) has a nearly constant residual of about 0.1 PgC per year, explained by the wetland methane emission of LPJ-GUESS that is not included in the coupling. This leak is of the order of the C4MIP drift limit of 10 PgC per century (Arora et al., 2026, preprint) and is being closed before the E-driven spin-up.

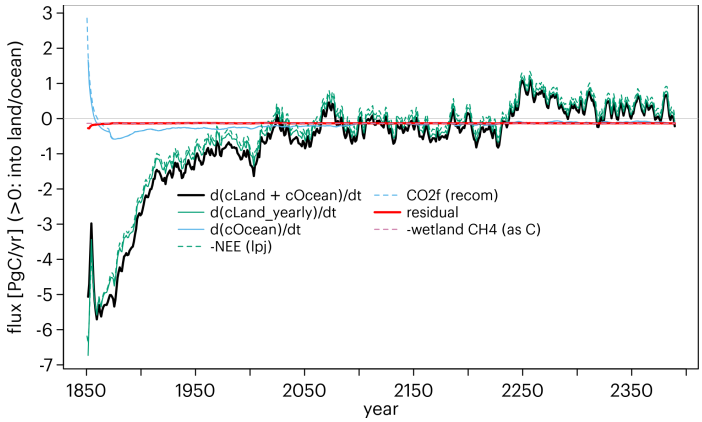


Fig. 3: Globally integrated C-driven piControl carbon budget of AWI-ESM-3-CC. The residual (red) is the sum of the changes in total land and ocean carbon (black) and the air–land (green dashed) and air–sea (blue dashed) CO_2 fluxes and equals the wetland methane emission missing in the coupling.

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