Final Report on “Impact of Greenland melt water on EC-Earth high resolution simulations”
Special Project spnldrij

Introduction
The original plan for this special project was to rerun EC-Earth in its PRIMAVERA configuration that was part of the CMIP6-HIGHRESMIP (Haarsma et al., 2016), and more specifically to its European branch “PRIMAVERA” funded by the EU (Haarsma et al., 2020). The work was intended to be carried out by Andre Juling and resulted in various paper with A. Juling as co-author.

The European Consortium Earth System Model in its PRIMAVERA setup precedes the EC-Earth3 version of CMIP6 in its standard- and high-resolution setup. The atmosphere component is cycle 36r4 of the Integrated Forecast System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF), the ocean model is NEMO3.6 (Barnier et al., 2006), the land model HTESSEL (Balsamo2009), and the Louvain-la-Neuve sea-ice model version 3 (LIM3; Vancoppenolle2012).
As part of the HighResMIP there are three EC-Earth3P-HR simulations: (1) control simulations using 1950 radiative forcing, (2) historical simulations from 1950-2015, and (3) projections of future climate change under the 2RCP8.5 scenario from 2015-2050 (Haarsma et al., 2016). There are three ensemble members each for each of the simulations (Haarsma et al., 2020); all the future simulations have since been extended to 2100.

Unfortunately, with the start of the project libraries and compilers at ECMWF were changed and the EC-Earth3P set-up was not updated, with the result that did no longer run. Since before devising new runs the old runs with EC-Earth3P were analysed with respect to implied mass loss from the large Ice Sheets in its control runs and with that information a Meltwater Release Protocol (MP) was devised before it could be added to the original EC-Earth3P runs, this inability to run EC-Earth3P any longer was detected late (after > 1 year), and a lot of time was wasted in fruitless attempts to compile and run EC-Earth3P, also not helped by the relocation of the ECWMF machines from Reading to Bologna. As a result, it was decided to change direction and make the MP available for EC-Earth3 where it contributed to the SOFIAMIP project (Swart et al., 2023); the updated EC-Earth3 version for EU-project OptimESM (Koenigk et al., 2023); and an improved model for the basalt melt of floating ice shelves Lambert et al. (20023, 2024). Below we discuss the main results that were realized within the special project spnldrij

Analysis of Previous EC-Earth3P simulations and Meltwater Release Protocol
First, the freshwater balance over the Antarctic (AIS) and Greenland (GrIS) Ice Sheets were analysed, being the balance in equilibrium, see Fig. 1.
Then the temperature evolution in EC-Earth3P is analysed, smoothed to fit a polynomial function (Fig. 3) for the relevant subregions of the AIS (Fig. 2) and the GrIS. Using Linear Response Functions of various stand-alone ice-sheet models between ocean temperature increase and mass loss we estimate the forcing functions for all subregions for EC-Earth3P based on different stand-alone ice-sheet models (Fig. 4). A slightly different approach is used for the GrIS where atmospheric warming is important for changes in runoff. Runoff is based on the Lenaerts et al. (2015) formula using a quadratic fit (R as a function of regionally averaged 500 hPa temperature T500) in 8 regions for run-off.
Discharge D: Either keep this constant or extrapolate recent trends.

An alternative approach is based on Noel et al (2021) providing an alternative regression based on the near-surface Greenland temperature wrt. pre-industrial, T_{GrIS}. Surface mass balance $SMB_{GrIS} = -10.27T_{GrIS}^2 - 51.7T_{GrIS} + 441.7$.

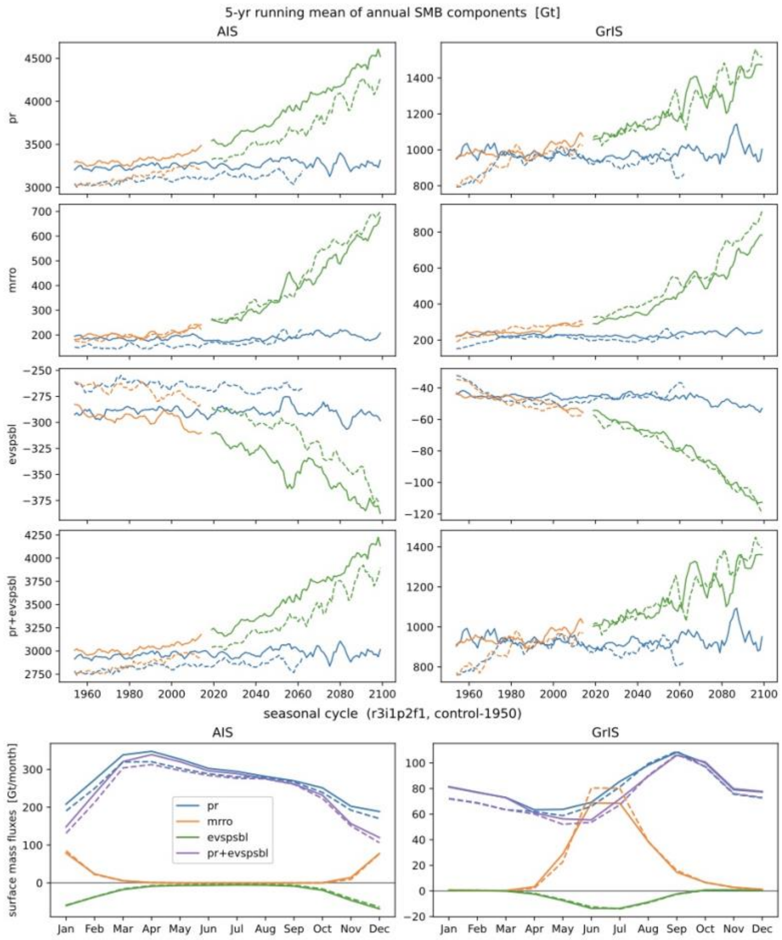

Figure 1. The surface mass balance for the AIS and GrIS in the EC-Earth3P runs without MP. (pr=precipitation; mrro=runoff, evspbl=evaporation+sublimation).

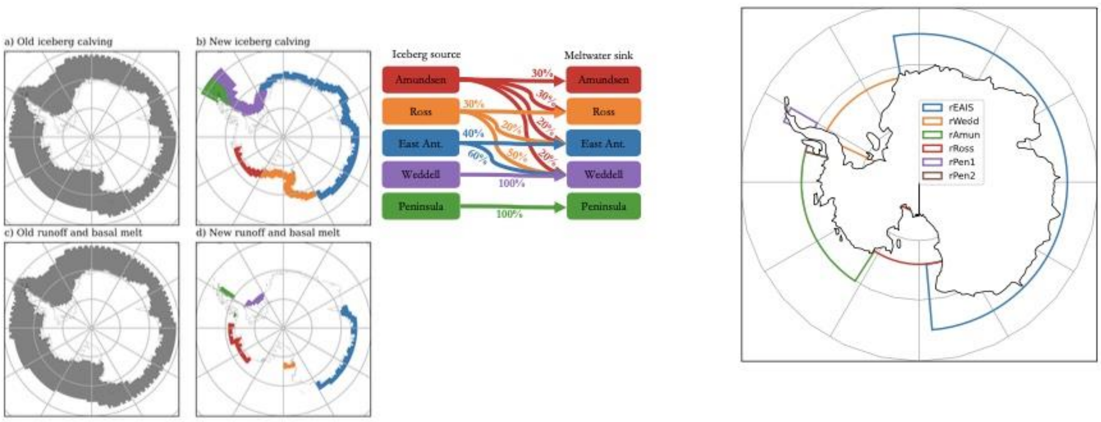

Figure 2. Maps and Masks for calving and ocean temperatures used for estimating basal melt for six regions of the AIS.

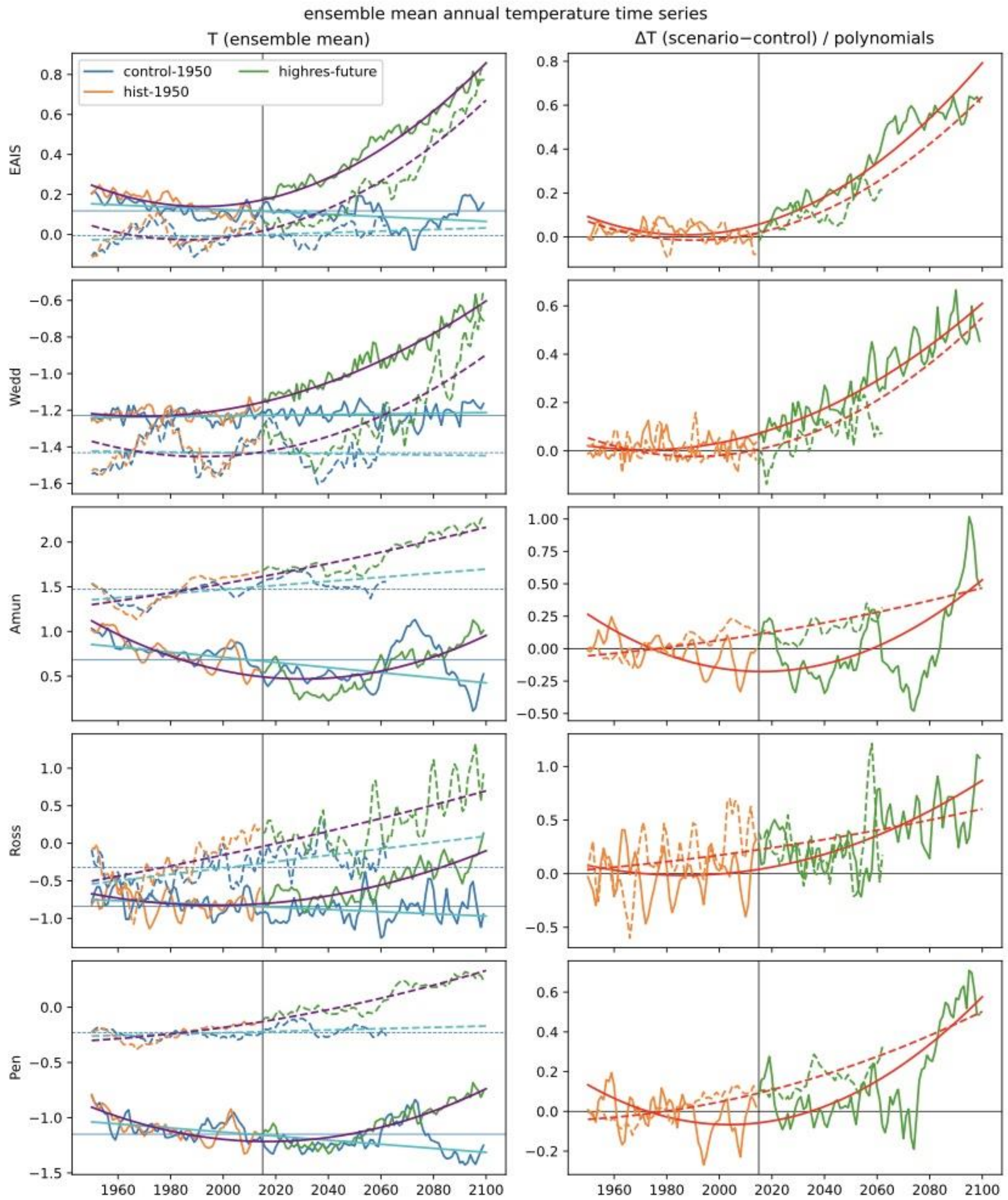

Figure 3. The ocean temperature evolution for the indicate regions in Fig. 2 in EC-Earth3P and the polynomial fit used for the Meltwater Release Protocol.

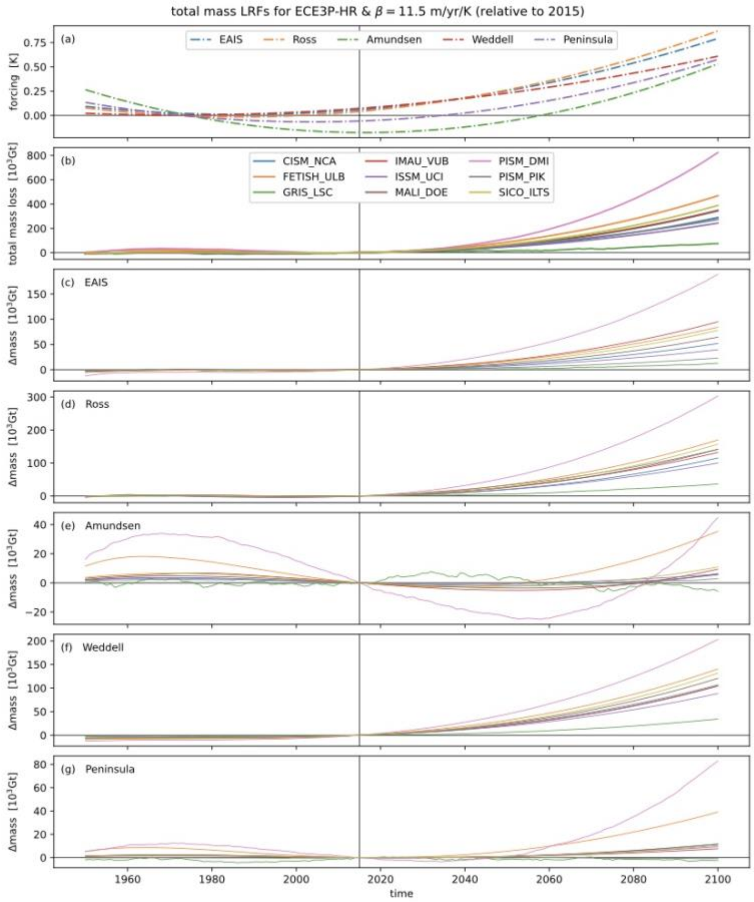

Figure 4. The response of the total mass loss for the various subregions of Antarctica for the polynomial temperature forcings of Fig. 3 based on different stand-alone ice-sheet models.

SofiaMIP

This model intercomparison project is about The Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative (Swart et al., 2023). Parts of the MP and associated analysis described above have been used in other coupled models to study the impact of Antarctic meltwater release on ocean deep convection and Antarctic Bottom Water Formation (Chen et al. 2023).

OptimESM

In this EU-project (Koenigk et al. 2023) the Meltwater Release Protocol was used to develop Linear Response Functions relating ocean temperature increase around Antarctica to basal melt and mass loss of the AIS (Fig. 5). These were then used to construct future projections of Antarctic mass loss for the various SSP scenarios (Fig. 6).

Modelling the basal melt of floating iceshelves

An improved model to translate the ocean temperature increase to increased basal met of floating iceshelves and land-ice has been developed to improve the MP to be used in EC-Earth3 and 4 (Lambert et al. 2023; Fig. 7).

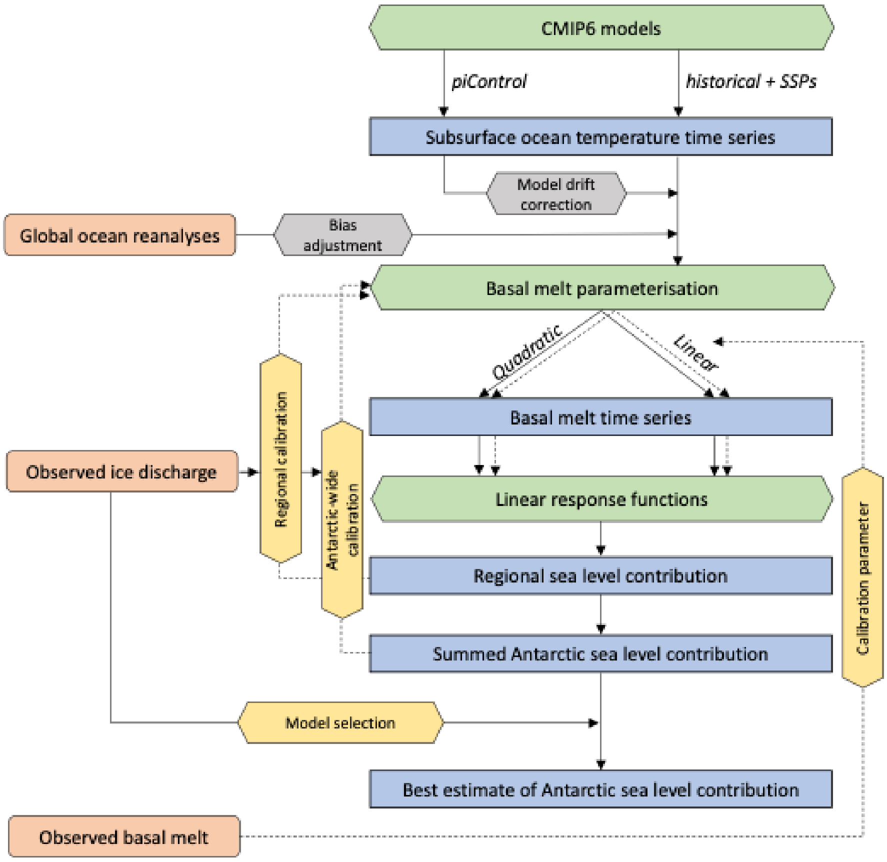

Figure 5. Flow diagram of procedure. Observational constraints are indicated in orange, main computations of the Levermann et al. (2020) method in green (including model experiments by the modelling groups), calibration methods in yellow, bias adjustments in grey and (intermediate) output data in blue. The continuous lines represent direct pathways while the dashed lines refer to iterative processes or optional choices during calibration.

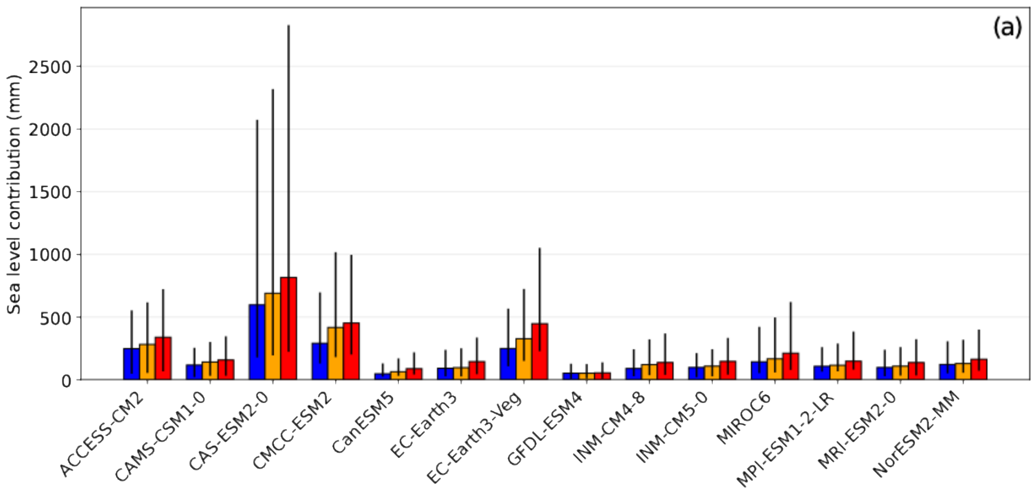

Figure 6. Projected Antarctic sea-level changes for SSP1-2.6 (blue), SSP2-4.5 (orange) and SSP5-8.5 (red) over the 21st century, defined as the difference between year 2100 and the period 1995-2014. Panel (a) shows the projections for each CMIP6 ESM, where the error bars indicate the 17th–83rd percentiles (computed from the associated RF time series).

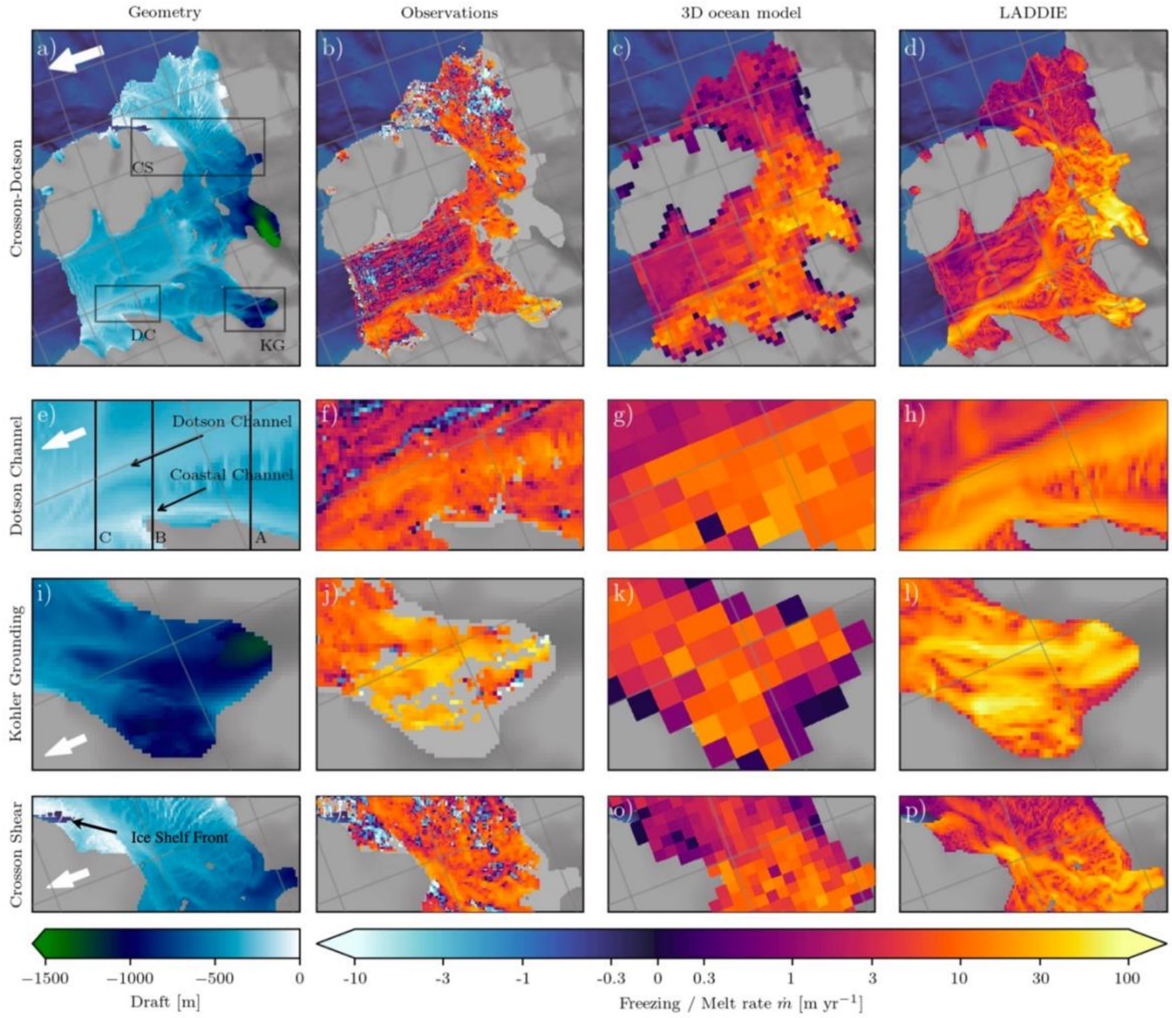

Figure 7. Spatial basal melt field of the Crosson–Dotson Ice Shelf. (a) Geometry in terms of ice shelf draft zb. Details of the insets are shown in subsequent rows, where DC is the Dotson Channel (shown in e–h), KG the Kohler grounding zone (i–l) and CS the Crosson shear margin (m–p). White arrows point north. (b) Observed basal melt rates from altimetry over the period 2010–2016 (c) Basal melt rates from a high-resolution 3D model. (d) Simulated basal melt rates using the improved basal melt model. The melt colour scale is a symmetrical log scale and is linear between values of −0.3 and 0.3 m yr^{-1}
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Feedback between meltwater release and ocean warming

Because meltwater release leads to fresh and buoyant surface water reduce mixing in the vertical, it is associated with further subsurface warming leading to even more meltwater release trough basal melt. An improved MP this includes this feedback, which was estimated using the MP discussed above to force EC-Earth3. The set-up for this extended protocol is shown in Fig. 8 and the impact on subsurface ocean warming in EC-Earth3 and projected sea-level rise due to Antarctic mass loss in Fig. 9.

Conclusion

Despite the inability to rerun EC-Earth3P and the necessity to change the original plan we managed in this special project to realize crucial progress in the treatment of ocean/ atmosphere interaction with the AIS and GrIS. The protocols developed here already have been partly used in the post-CMIP6 version of EC-Earth3 used in the EU-funded program OptimESM and will become (are now becoming) part of EC-Earth4 and CMIP7.

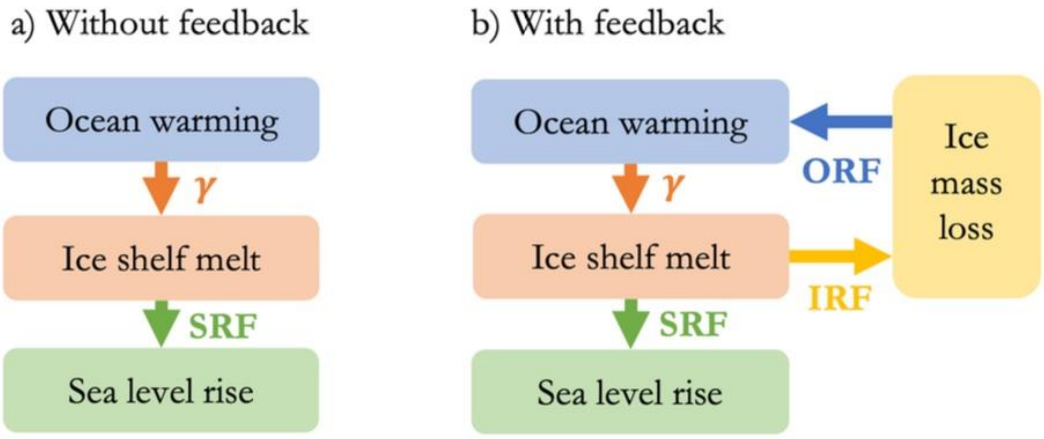

Figure 8. Two methods to compute the Antarctic sea-level contribution from ocean warming. a) Method of Levermann et al. (2020) without feedbacks. b) Expanded method accounting for the potential feedback between mass loss and ocean warming. SRF: Sea-level Response Function. IRF: Ice mass Response Function. ORF: Ocean Response Function.

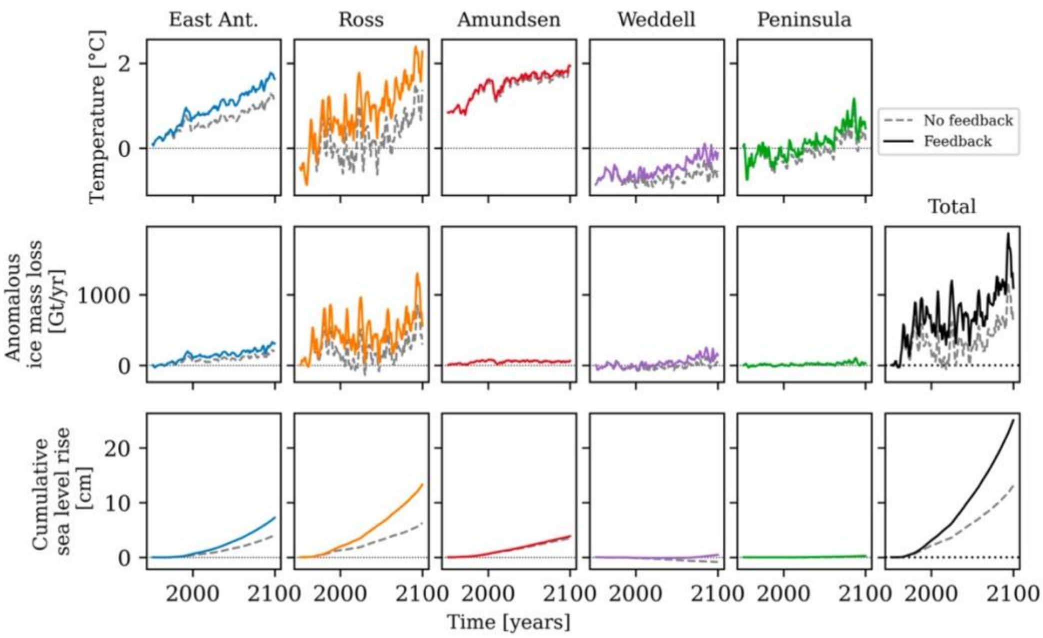

Figure 9. Impact of feedback on a single ensemble member based on the temperature projection from EC-Earth3 under SSP2-4.5, IRF and SRF from a stand-alone ice-sheet model and with quadratic basal melt parameterisation. Time series are shown for subsurface temperature, cumulative ice mass loss, and cumulative sea-level rise from five regions. The grey lines indicate the response without feedback. Coloured lines indicate the response including the feedback.

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