



## TIPMIP-OCEAN experimental protocol phase 2: Southern Ocean and Combined Dual-Hemispheric Freshwater Forcing

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**Abstract.** This paper describes the experiment protocol for coordinated simulations of Southern Ocean and combined dual-hemispheric (Southern Ocean and North Atlantic) ice sheet meltwater flux perturbations. These simulations form the second phase of the TIPMIP-OCEAN domain as part of the international Tipping Points Modelling Intercomparison Project (TIPMIP). We propose that the experiments are included in the Coupled Model Intercomparison Project Phase 7 (CMIP7), although any emission-driven Earth System Models can implement the protocol. The experimental design complements the first phase of the TIPMIP-OCEAN domain experiments which address the response of the North Atlantic to various amounts of Greenland Ice Sheet meltwater at different levels of global warming. Here we propose a similar protocol exploring the impact of freshwater fluxes from the Antarctic Ice Sheet into the Southern Ocean. Further, the impact of freshening in both hemispheres is examined,



through simultaneous freshwater release around Greenland and off the coast of Antarctica. Together with the North Atlantic hosing simulations, our proposed experiments will assess the combined impact of freshening in both hemispheres on the stability of the Atlantic Meridional Overturning Circulation (AMOC) and Southern Ocean Abyssal Circulation (SOAC), and their associated potential tipping mechanisms and impacts on the Earth system.

## 1 Introduction

Tipping points in the climate system are critical thresholds beyond which the system reorganises from one stable state to another, irreversibly and/or abruptly, either due to external forcing or internal dynamics (Winkelmann et al., 2025). With ongoing climate change, the likelihood of crossing tipping thresholds increases, and several tipping elements are already undergoing pronounced changes under current warming levels (Scheffer et al., 2001; Lenton et al., 2008; Armstrong McKay et al., 2022). Tipping elements interact across different spatial and temporal scales and, although there is increasing evidence for tipping cascades (Wunderling et al., 2024; Swingedouw et al., 2020), their likelihood, consequences, and timescales remain to be fully understood.

Among the core climate tipping elements are the Atlantic Meridional Overturning Circulation (AMOC), Southern Ocean Abyssal Circulation (SOAC), the Greenland Ice Sheet (GIS), and the West Antarctic Ice Sheet (WAIS) (Armstrong McKay et al., 2022). Despite interacting on very different timescales, these elements can either amplify or dampen each other's stability (Pöppelmeier and Stocker, 2025). Ongoing climate change is accelerating melt of the Antarctic and Greenland ice sheets (e.g., Paolo et al., 2015; Otosaka et al., 2026; Bonsoms et al., 2026), resulting in increased freshwater input into the Southern Ocean, North Atlantic and Arctic Oceans, respectfully.

The Southern Ocean plays a key role in the climate system, modulating global heat, nutrient, oxygen, and carbon budgets through the upwelling of deep waters and the formation of mode, intermediate, and bottom waters (Sarmiento et al., 2004; Sallée et al., 2010; Frölicher et al., 2015; Menviel et al., 2026). On Antarctic continental shelves, continuous sea ice formation and strong katabatic winds produce extremely cold and salty water masses that sink along the continental slope into the deep ocean (e.g., Johnson, 2008). This Antarctic Bottom Water ventilates the abyss and stores heat and carbon, and as it spreads northward, it forms the lower limb of the global Meridional Overturning Circulation (MOC). The SOAC is projected to weaken dramatically this century, or even collapse, depending on the rates of warming of Antarctic shelf waters, sea-ice formation and freshening due to ice sheet and ice shelf melt, and potentially faster than the anticipated slowdown of the AMOC (Menviel et al., 2026; Li et al., 2023; Abram et al., 2025; Purich and England, 2021). The weakened SOAC leads in turn to reduced ventilation at depth (Gunn et al., 2023), weaker ocean carbon uptake (Liu et al., 2023) and enhanced deoxygenation (Frölicher et al., 2020). Simulations using observed or projected future freshwater fluxes have shown that increasing AIS meltwater runoff leads to sea surface cooling and localised sea ice expansion in the Southern Ocean, as well as subsurface mid-to deep ocean warming and a reduction of Antarctic Bottom Water formation (Bronselaer et al., 2018; Mackie et al., 2020; Chen et al., 2023; Swart et al., 2023; Schmidt et al., 2023; Muilwijk et al., 2026). Subsurface warming could establish a positive feedback whereby increasing melt drives increasing freshwater fluxes, which reinforce subsurface warming, and further accelerate melt



(Golledge et al., 2014, 2019; Kreuzer et al., 2026; Li et al., 2024). Given the high sensitivity of Antarctic Ice Sheet mass loss to ocean warming (e.g. Reese et al., 2017), such a feedback would substantially increase the risk of crossing critical thresholds of the AIS. Of particular concern in this respect are recent assessments indicating that less than 1°C additional ocean warming  
 45 above present-day may be sufficient to trigger tipping of the WAIS, resulting in a sustained sea-level contribution of ca. 4 m (Golledge et al., 2021; Rosier et al., 2021; Chandler et al., 2025; Winkelmann et al., 2026).

Considerable uncertainty remains in the assessment of the SOAC as a tipping element in Earth System Models (ESMs), due to unrealistic open ocean convection, fixed-volume ice sheets, unresolved Antarctic Slope Current, eddies, and tides, and an inadequate representation of ice shelf meltwater production and export (Heuzé, 2021; Abram et al., 2025; Purich and England,  
 50 2021). Idealized freshwater perturbation experiments are often used to overcome the lack of interactions between the Antarctic Ice Sheet (AIS) and the ocean in most numerical simulations (e.g., Richardson et al., 2005; Bronselaer et al., 2018; Li et al., 2023; Mackie et al., 2020; Swart et al., 2023). The Southern Ocean Freshwater Input from Antarctica (SOFIA) framework (Swart et al., 2023) has now formalised a consistent experimental design of freshwater release experiments in the Southern Ocean to reconcile previous studies and quantify robust imprints of enhanced Antarctic ice sheet melt on the Earth system.  
 55 Early results of simulations based on a pre-industrial climate and spatially uniform and temporally constant freshwater forcing around Antarctica show reduced open-ocean deep convection, leading to a warming of Antarctic Bottom Water and sea surface cooling, whereby the magnitude of the response depends strongly on modelled mean-state climatology (Chen et al., 2023). The freshwater forcing further results in asymmetric temperature feedbacks, in which this positive feedback between ice loss and subsurface warming is strongest in East Antarctica (Muilwijk et al., 2026). Beyond the regional effects, Southern Ocean  
 60 freshwater forcing impacts tropical climate through coupled atmosphere-ocean interactions, though the proposed teleconnection mechanisms lack robustness between models (Zhang et al., 2026). SOFIA tier 2 experiments combine freshwater forcing with historical and scenario forcings (SSP1-2.6 and SSP5-8.5) but do not explore the reversibility and potential carbon cycle feedback responses to increasing freshwater.

From the Southern Ocean, upper and intermediate waters flow northward in the Atlantic Ocean, where they eventually cool,  
 65 sink, and return southward at depth as the lower limb of the AMOC. The AMOC is maintained by a positive salt-advection feedback, in which the northward transport of salt sustains high surface salinities and hence densities necessary to precondition convective areas for dense water formation (Stommel, 1961; Rahmstorf, 1996; Weijer et al., 2019). As such, warming, and freshwater anomalies due to Arctic freshwater input, GIS mass loss (e.g., Ravinder et al., 2024), and changes in the hydrological cycle, that reduce surface salinity and density, can suppress the buoyancy-driven convection and associated formation of North  
 70 Atlantic Deep Water (Bakker et al., 2016). Many ESMs have shown that the AMOC is sensitive to changes in the freshwater balance in the North Atlantic (Weijer et al., 2019; Dijkstra et al., 2026), either in emission scenarios that project changes in the freshwater cycle in response to anthropogenic forcing until the end of the 21st century (e.g., Weijer et al., 2020; Drijfhout et al., 2025), or in targeted hosing experiments that prescribe anomalous freshwater fluxes (e.g., Jackson and Wood, 2018; Orihuela-Pinto et al., 2022; van Westen and Dijkstra, 2023). The response timescale and the potential reversibility of AMOC weakening  
 75 in such hosing experiments remain under debate and may depend on the strength, timing, and location of the freshwater forcing. For moderate freshwater forcing below 0.1 Sv, the weakening timescale is set by the rate of freshwater input and can exceed a



century, as feedbacks that hinder reversibility are avoided (Jackson and Wood, 2018; Martin et al., 2022). For forcing of 0.3 Sv or more, the timescale shortens to a few decades and may become insensitive to the forcing rate (Jackson and Wood, 2018), as well as leading to pronounced hysteresis when forcing is reversed (van Westen and Dijkstra, 2023). The projected weakening of the AMOC has also been shown to be more pronounced if freshwater fluxes are added into the Irminger Basin instead of the Labrador Sea, Nordic Seas or the North-East Atlantic (Ma et al., 2024).

To assess the sensitivity of the AMOC to freshwater forcing across models, the North Atlantic Hosing Model Intercomparison Project (NAHosMIP, Jackson et al., 2023) and more recently, TIPMIP-OCEAN (Swingedouw et al., 2026) have formalised North Atlantic freshwater release experiments. Within NAHosMIP experiments, constant freshwater fluxes are applied for a fixed period of time (Jackson et al., 2023). TIPMIP-OCEAN is part of the Tipping Points Modelling Intercomparison Project (TIPMIP, Winkelmann et al., 2025) that systematically explores the tipping dynamics of Earth System components, organised through various domains. Within the TIPMIP-ESM domain, fully coupled Earth System Models are run following a ramp-up, zero-emission, and ramp-down climate scenario (Jones et al., 2026). Complementing the TIPMIP-ESM Tier 1 simulations, the TIPMIP-OCEAN domain, in its first phase, proposes simulations following the same climate pathway, while including freshwater forcing locally around Greenland and more widely in the Northern hemisphere. These simulations allow specific assessment of the stability, abrupt changes, and reversibility of the AMOC under combined CO<sub>2</sub> and increasing, constant, and decreasing North Atlantic freshwater hosing (Swingedouw et al., 2026). In contrast to both the SOFIA framework as well as NAHosMIP, the CO<sub>2</sub> emission-driven simulations within TIPMIP-OCEAN allow carbon-climate interactions and feedbacks to be resolved interactively (Sanderson et al., 2024).

The climate responses to freshening are not hemispherically confined: the impacts of Antarctic freshwater fluxes can extend to the Northern Hemisphere mid-latitudes or even Arctic (e.g., Richardson et al., 2005; Bronselaer et al., 2018; Mackie et al., 2020), while North Atlantic freshwater fluxes can drive responses in the Southern Ocean through interhemispheric oceanic and atmospheric teleconnections (Timmermann et al., 2010; Orihuela-Pinto et al., 2022; Liu et al., 2020; Pedro et al., 2018; Diamond et al., 2025; Höse et al., 2026). For example, changes in Southern Hemisphere sea ice cover driven by Antarctic meltwater can modify large-scale atmospheric circulation patterns (Swingedouw et al., 2008), with implications for Northern Hemisphere climate and the AMOC (e.g., Gülk et al., 2026). Moreover, freshwater released around Antarctica may eventually be transported into the North Atlantic on multidecadal timescales, where it can directly affect AMOC stability (Stouffer et al., 2007; Swingedouw et al., 2009). Vice versa, a weakening of the AMOC has been shown to reduce northward ocean heat transport, which subsequently leads to warming in the South Atlantic, increased Southern Ocean sea surface temperatures and Antarctic sea ice loss on multi-decadal timescales (Stocker and Johnsen, 2003; Pedro et al., 2018; Diamond et al., 2025). Integral to the interhemispheric coupling is a compensating atmospheric heat transport in response to large-scale circulation change (Zhang et al., 2017; Pedro et al., 2018); however, there remains a need to better constrain how e.g. the Intertropical Convergence Zone (ITCZ) position responds to both warming and to a slowdown of the AMOC and SOAC. Consistent with a weakened state of the AMOC is a southward shift of the ITCZ, in particular over the Atlantic (e.g., Guo et al., 2026), while increased meltwater in the Southern Ocean potentially leads to a northward shift of the ITCZ (Purich and England, 2023).



Together, these interhemispheric climate responses highlight the potential for complex interactions on varying timescales arising from the simultaneous increase in both Greenland and Antarctic freshwater fluxes — a scenario that has received comparatively little attention. Freshwater hosing experiments have begun to explore these dynamics (Stouffer et al., 2007; Swingedouw et al., 2009; Menviel et al., 2010; Hu et al., 2013; Li et al., 2024), and projections of future Southern Ocean meltwater fluxes suggest their impact on global climate will intensify (Li et al., 2023; Purich and England, 2023; Sadai et al., 2025). Recent modelling with an ESM of Intermediate Complexity (EMIC) indicates that WAIS meltwater input can either increase or decrease AMOC resilience to GIS-sourced freshwater forcing, depending on the relative timing and magnitude of the two signals (Sin et al., 2025), although this remains to be assessed with ESMs. However, few studies have examined this interaction systematically, or addressed its implications for ocean carbon cycling, or tested the reversibility of the coupled circulation response. Moreover, the individual impacts of increasing freshwater fluxes through ice sheet melt have been studied more extensively in the Northern Hemisphere than in the Southern Hemisphere, though with considerable remaining uncertainty; interactions between the responses to increasing freshwater fluxes from both ice sheets are even less well understood (van den Berk et al., 2019; Li et al., 2024). So far, no coordinated multi-model experiment has examined the simultaneous release of freshwater in both hemispheres. Moreover, the effects of Southern Ocean freshwater release have not been systematically explored in an emission-driven modelling framework and under zero emission conditions. Therefore, we propose three experiments designed to bridge the TIPMIP and SOFIA communities.

1. Experiment A aims to examine the Earth system response to Southern Ocean freshwater input under increased global temperatures. The experiment follows the TIPMIP-ESM temperature forcing pathways of Jones et al. (2026), combined with a Southern Ocean freshwater forcing based on a protocol similar to that of the TIPMIP-OCEAN phase 1 freshwater release experiment A of Swingedouw et al. (2026).
2. Experiment B aims to examine the Earth system response to dual-hemispheric freshwater forcing under increased global temperatures. The experiment combines the Southern Ocean freshwater forcing from Experiment A with North Atlantic freshwater forcing following TIPMIP-OCEAN phase 1 freshwater release experiment A (Swingedouw et al., 2026), together with the TIPMIP-ESM temperature forcing pathways of (Jones et al., 2026).
3. Experiment C bridges the gap to SOFIA (and the SOFIAMIP tier 1 for CMIP7) by largely following their tier 1 protocol (Swart et al., 2023), meaning (near-)coastal release of 0.1 Sv of freshwater uniformly distributed around Antarctica maintained for at least 100 years under pre-industrial conditions, and providing a baseline without additional forcing except for the freshwater added in the Southern Ocean.

This second phase of TIPMIP-OCEAN establishes a protocol that focuses more strongly on the Southern Ocean and its role for global climate. The experiments will allow us to assess how idealised freshwater fluxes from one ice sheet influence the climate response to freshwater fluxes from the other, and whether the combined responses are additive, synergistic, or opposing. Further, the reversibility of the Earth System impacts of warming and freshening, applied in the Southern Ocean alone or in both hemispheres, can be assessed. By adopting an emission-driven framework, these experiments include interactive carbon-



climate feedbacks. This will allow evaluation of the effects of changes in stability of the SOAC and the AMOC, on the net  
 145 ocean and land carbon sinks, as well as cascading effects within the Earth System.

## 2 Experimental design

### 2.1 General description

Our proposed experiments aim to complement the TIPMIP-ESM protocol (Jones et al., 2026) and TIPMIP-OCEAN phase  
 1 (Swingedouw et al., 2026) and bridge the gap to SOFIA (Swart et al., 2023). The experiments allow assessment of the  
 150 robustness of the simulated impacts of 1) freshwater input in the Southern Ocean, and 2) freshwater input in both hemispheres.  
 This simple and consistent protocol allows participation by many modelling groups. The three proposed experiments A, B and  
 C are described in more detail here.

As a baseline and control for experiments A and B, we use the ramp-up to the global warming level (GWL) of 2°C, sta-  
 bilisation, and ramp-down of greenhouse emissions from the TIPMIP-ESM protocol (Jones et al., 2026). Starting from the  
 155 emission-driven pre-industrial control simulation, the ramp up is forced by a CO<sub>2</sub> emission rate of X GtC yr<sup>-1</sup> so that global  
 mean surface air temperature (GMSAT) increases by 2°C +/- 0.1°C per century, with X being diagnosed by the model-specific  
 transient temperature response to cumulative carbon emissions (TCRE, Allen et al., 2009; Arora et al., 2020). Centred 31-year  
 running mean GMSATs compared to the pre-industrial GMSAT are used to evaluate the time when the GWL=2°C is reached  
 in the TIPMIP-ESM ramp up simulation. Because of model internal variability, the GWL=2°C might not be reached exactly  
 160 after 100 years, but after 100±n years. After 100±n years, a zero emission run is branched off that stabilises GMSAT around  
 GWL=2°C (Jones et al., 2026). After 50 years with zero emissions, negative emissions are applied with -X GtC yr<sup>-1</sup>, until the  
 pre-industrial GMSAT is reached again after approximately 100 years, i.e., after 100±m years.

We further encourage that all participating modelling groups have run Experiment A of TIPMIP-OCEAN phase 1 in Swinge-  
 douw et al. (2026). This experiment applies a ramp-up, stable, and ramp-down freshwater forcing around Greenland and follows  
 165 strictly the emission trajectory of the TIPMIP-ESM protocol. Next to experiment A, the experiment serves as another coun-  
 terfactual simulation to our proposed experiments B, allowing us to disentangle the effects of hosing in the North Atlantic,  
 Southern Ocean and both hemispheres. We require strict adherence to both protocols to ensure comparability.

For experiment C, the emission-driven pre-industrial control simulation serves as a baseline.

### 2.2 Experiments

#### 170 2.2.1 Experiment A: ramp-up, stabilisation, and ramp-down of greenhouse emissions and Southern Ocean freshwater release

Experiment A applies freshwater forcing off the coast of Antarctica (see section 2.3) and is motivated by the different sub-  
 experiments as outlined in Swingedouw et al. (2026) for their Experiment A. Essentially, freshwater forcing is linearly in-  
 creased from 0 until 0.3 Sv over approximately 100 years, in tandem with the increasing CO<sub>2</sub> emissions. After 50 years of



175 constant 0.3 Sv freshwater fluxes and zero CO<sub>2</sub> emissions, the freshwater forcing is decreased from 0.3 Sv to 0 Sv, while negative CO<sub>2</sub> emissions are applied. The freshwater perturbations are applied over a mask that is wider than in the SOFIA tier-1 *antwater* experiment, where freshwater is added to the ocean cells adjacent to Antarctica, but much narrower than in the tier-3 *antwater-60s* experiment, where it is applied uniformly south of 60°S (Swart et al., 2023).

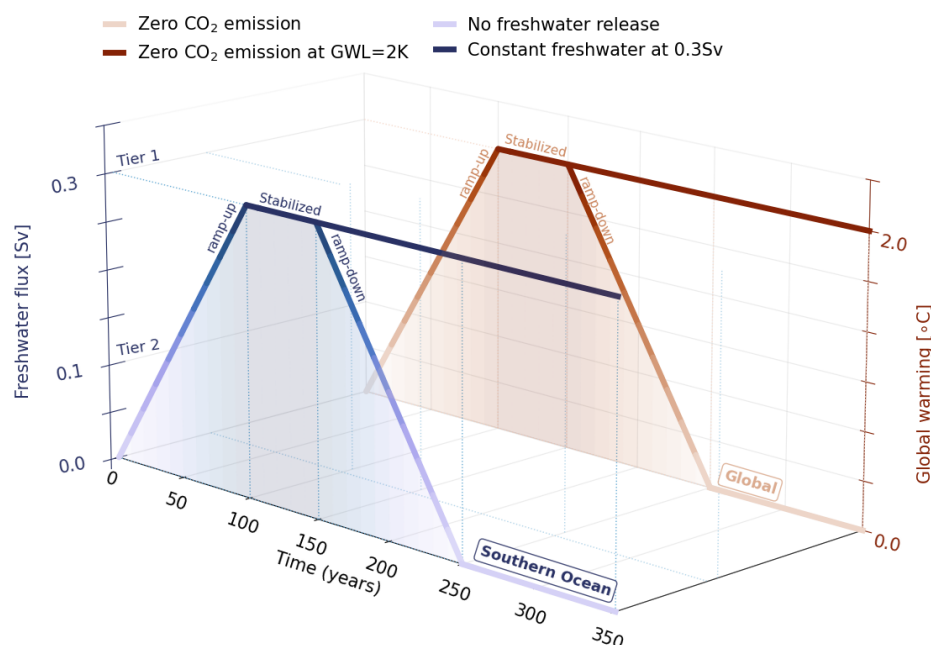


**Figure 1.** Schematic of the protocol of Experiment A simulations with 0.3 Sv freshwater forcing (blue lines, tier 1) in the Southern Ocean and CO<sub>2</sub> emissions equivalent to global warming (red lines). Note that the GMSATs in the stabilised scenario with freshwater forcing will likely not reach 2°C after 100 years of positive emissions due to the simultaneously applied freshwater forcing. Adapted from Swingedouw et al. (2026) and Jones et al. (2026).

The Experiment A tier 1 protocol is as follows (see also Table 1 and Figure 1):

1. Starting from the emission-driven pre-industrial control simulation, CO<sub>2</sub> emissions are set to achieve 0.2°C warming per decade following the same CO<sub>2</sub> emissions rate of X GtC yr<sup>-1</sup> as used in the TIPMIP-ESM Tier 1 *esm-up2p0* simulation (Jones et al., 2026). As in Swingedouw et al. (2026), simultaneously, a prescribed freshwater flux is added to the surface of the Southern Ocean that increases from 0 Sv at year=0 to +0.3 Sv in year=100±n. The simulation length of 100±n



years is set by the time at which the GWL of  $2^{\circ}\text{C}$  is reached in the TIPMIP-ESM *esm-up2p0* simulation. Note that due to the added freshwater forcing, the GWL= $2^{\circ}\text{C}$  will not be reached at the same time of  $100\pm n$  years.

2. A zero-emission run is branched off on January 1st in year  $100\pm n+1$  (after GWL= $2^{\circ}\text{C}$  is reached in the TIPMIP-ESM *esm-up2p0-gwl2p0* simulation), while retaining a  $+0.3$  Sv freshwater flux in the Southern Ocean. The run is 250 years long.
3. A negative emission run is branched off after 50 years of zero-emissions with the same rate of negative  $\text{CO}_2$  emissions of  $-X \text{ GtC yr}^{-1}$  from the *esm-up2p0-gwl2p0-50y-dn2p0* simulation in the TIPMIP-ESM protocol (Jones et al., 2026) and a decreasing freshwater flux from  $+0.3$  Sv to 0 Sv after  $100\pm m$  years in the Southern Ocean. The simulation length of  $100\pm m$  years is set by the time at which the GWL of  $0^{\circ}\text{C}$  is reached in the TIPMIP-ESM *esm-up2p0-gwl2p0-50y-dn2p0* simulation.
4. The run is extended for 100 years after GWL= $0^{\circ}\text{C}$  is reached in the TIPMIP-ESM *esm-up2p0-gwl2p0-50y-dn2p0* simulation, with emissions set to 0 and the freshwater flux set to zero.

We request for tier 1 experiments a large freshwater flux of 0.3 Sv, first to ensure a strong response, and second, to remain consistent with tier 1 of the TIPMIP-OCEAN protocol. This forcing is comparable to some higher-end Southern Ocean hosing experiments under the CMIP5/6 RCP8.5 and SSP5-8.5 scenarios (e.g., Bronselaer et al., 2018; Purich and England, 2023), while the SOFIA tier 2 ssp585-ismip6-water experiment (Swart et al., 2023) reaches  $+0.2$  Sv by 2100. Although this forcing is reasonable for an idealistic experiment, we note that freshwater fluxes projected by Coulon et al. (2024) under SSP5-8.5 only reach  $+0.3$  Sv in the mid 2200s, when GMSAT is likely to have increased by far more than  $2^{\circ}\text{C}$  (for example, near  $8^{\circ}\text{C}$ : Goelzer et al., 2025).

Because the ramp up from TIPMIP-ESM might not be exactly 100 years, but  $100\pm n$  years, the hosing increment in the ramp up needs to be adjusted accordingly to freshwater release by  $0.3/(100\pm n)$  Sv. The same adjustment applies to the ramp-down, following the same length as the TIPMIP-ESM ramp down simulations, i.e.,  $100\pm m$  years. Note that the added freshwater might itself impact global climate, and so the GWL= $2^{\circ}\text{C}$  might not be reached at the same time as in the TIPMIP-ESM *esm-up2p0* simulation.

The experiments are designed for model configurations without interactive ice sheets. Some model systems incorporate a coupled GIS and/or AIS (e.g., Muntjewerf et al., 2021; Smith et al., 2021; Madsen et al., 2022; Goelzer et al., 2025; Sadai et al., 2025). Others simulate AIS mass loss with freshwater emulators, such as the Antarctic Ice Melt Emulator (AIMS) coupled in EC-Earth3-ESM (van der Linden et al., 2026). In these systems, the total freshwater flux from the ice sheet might be higher than that in the uncoupled (non-interactive) systems. However, we encourage the modelling groups to follow the same protocol here to ensure the same forcing anomaly, and thus comparability to other participating models.

As tier 2 experiments, we propose to reduce the freshwater forcing to 0.1 Sv. This provides a less extreme forcing than tier 1 and also matches the SOFIA tier 1 and tier 3 experiments (Swart et al., 2023), as well as the TIPMIP-OCEAN tier 2 experiment A (Swingedouw et al., 2026). Compared to observational data, this forcing is still on the higher side, i.e. the mass loss from



grounded and floating ice shelves into the Southern Ocean in the 2010s has been estimated to be of the order of  $0.017 \pm 0.006$  Sv (Slater et al., 2021; Swart et al., 2023).

We do not know in advance whether the SOAC and its associated deep water formation will collapse in response to an additional freshwater flux of 0.3 Sv in the Southern Ocean. As a tier 4 experiment, we therefore propose that modelling centres increase the freshwater hosing to an even higher level, of their choice, to ensure a collapse of the Southern Ocean abyssal circulation. This will allow us to study the resulting climate and Earth system response and potential cascading impacts of crossing this tipping point. This higher flux is model dependent and also rate dependent: in the ACCESS-ESM1.5 model, for example, AABW formation nearly shuts down when 0.55 Sv of Antarctic meltwater is added, whereas with a smaller freshwater flux of 0.18 Sv, AABW formation slows and eventually collapses, but later and more gradually (Purich and England, 2023).

Another potential extension of our protocol is the use of freshwater fluxes associated with potential tipping dynamics of the AIS as estimated in TIPMIP-ICE SHEETS (Winkelmann et al., in prep). The TIPMIP-ICE SHEETS experiments may produce mean realistic freshwater fluxes, as well as upper and lower boundaries thereof, whose impacts on the Earth System could be explored in tier 4 experiments within this protocol.

We request only one ensemble member per model for tier 1 experiments, to maximise the number of participating modelling groups. We acknowledge that a larger ensemble size would better sample model uncertainty and internal variability, which may be particularly important for assessing the probability of rare tipping events. For example, Romanou et al. (2023) show that the AMOC tipping threshold is highly sensitive to the state of internal variability at the time of forcing in the 10-member ensemble simulation with the NASA GISS-E2-1-G climate model.

To summarize the potential extensions to the tier 1 protocol, we therefore suggest that modelling groups consider to run tier 2, tier 3 or tier 4 experiments if resources allow. Note that the number of the tier does not reflect any prioritisation:

1. Run the same protocol but with a smaller freshwater flux of 0.1 Sv, which matches the SOFIA tier 1 and tier 3 experiments, and bridges to Experiment C (tier 2).
2. Run the same protocol but with a higher freshwater flux that will force a collapse of the Southern Ocean abyssal circulation. The amount of freshwater is model-dependent and would need to be chosen by individual modelling groups (tier 3).
3. Run the same protocol but with a more realistic freshwater flux provided by TIPMIP-ICE SHEETS (tier 4).
4. Run the same protocol but with more ensemble members of the tier 1 or lower tier runs branched off at different years of the emission driven pre-industrial control simulation.

#### **2.2.2 Experiment B: ramp-up, stabilisation, and ramp-down of greenhouse emissions and dual-hemispheric freshwater release**

Experiment B is the dual hemispheric hosing experiment that follows the exact same protocol as experiment A for tier 1 and lower tier experiments, but also adds freshwater off the coast of Greenland (see also Table 2 and Figure 3). The idealized



freshwater perturbations in the North Atlantic are applied using the same spatial mask used in the NAHosMIP (Jackson et al.,  
 250 2023) and TIPMIP-OCEAN (Swingedouw et al., 2026) that was based on the CORE3 protocol (Gerdes et al., 2006). Note that  
 for tier 1 experiments in experiment B the total maximum global freshwater forcing is 0.6 Sv, i.e., 0.3 Sv from each ice sheet.

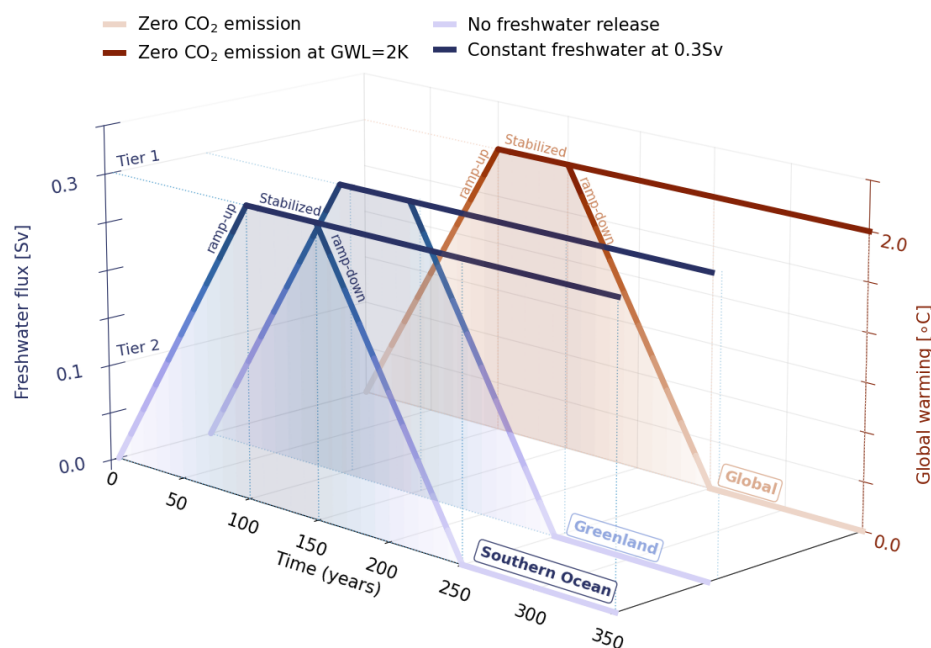


**Figure 2.** Schematic of the protocol of Experiment B simulations with 0.3 Sv freshwater forcing (blue lines, tier 1) in the Southern Ocean and around Greenland and CO<sub>2</sub> emissions equivalent to global warming (red lines). Note that the GMSATs in the stabilised scenario with freshwater forcing will likely not reach 2°C after 100 years of positive emissions due to the simultaneously applied freshwater forcing. Adapted from Swingedouw et al. (2026) and Jones et al. (2026).

### 2.2.3 Experiment C: Baseline step function

Experiment C closely follows the *antwater* experiment of the SOFIA tier 1 protocol (Swart et al., 2023). However, instead of  
 adding all the freshwater to coastal grid cells (as requested for the *antwater* experiment), we request that freshwater is added  
 255 using the tapering function of Equation (1) (see Section 2.3 below). By using the tapering function, our protocol represents an  
 intermediate between the SOFIA tier-1 *antwater* and tier-3 *antwater-60s* experiments.

The Experiment C protocol is as follows and illustrated in Figure 3:



1. Starting from the emission-driven pre-industrial control simulation, a prescribed freshwater flux is continuously added uniformly to coastal ocean grid cells around Antarctica at a constant rate of 0.1 Sv over 100 years.

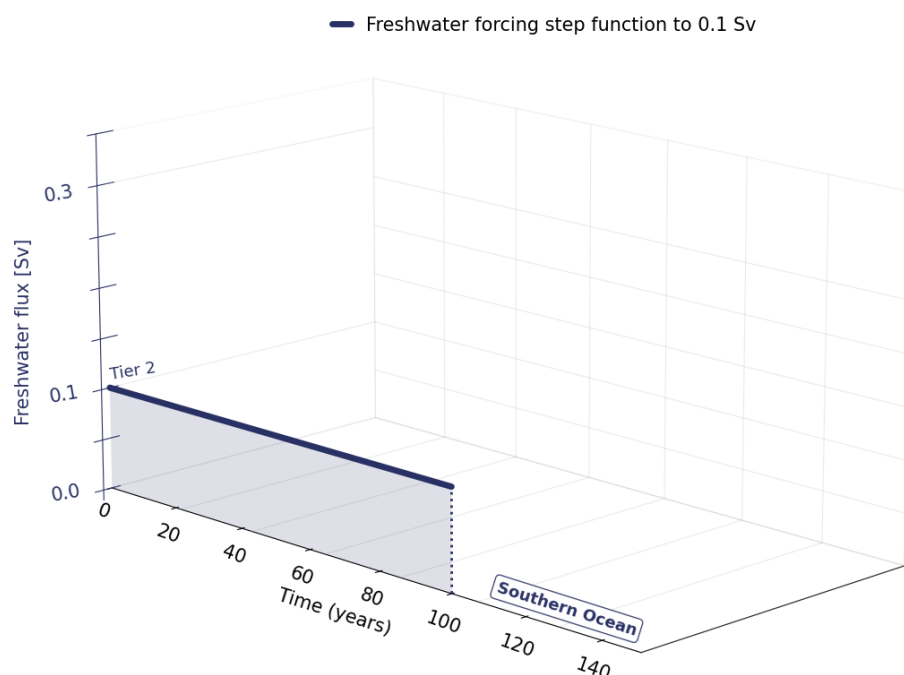


**Figure 3.** Schematic of the protocol of Experiment C simulations with 0.1 Sv freshwater forcing as a step function (blue lines, tier 2) in the Southern Ocean.

260 Experiment C is considered as a tier 2 experiment. So far, there is limited overlap between the models that participate in TIPMIP-OCEAN and SOFIA. Therefore, we ask for this short, simple baseline experiment to clearly connect the two multi-model ensembles, lending comparability and additional credibility to the results of both efforts and also feeding into SOFIAMIP for CMIP7 (their tier 1) (Swart et al., 2023).

### 2.3 Definition of hosing fields

265 The three proposed experiments here apply freshwater fluxes in the Southern Ocean around Antarctica, or in both hemispheres simultaneously, to mimic increasing ice sheet meltwater runoff. The most physically realistic approach to apply freshwater



hosing is to add the additional freshwater directly as a freshwater flux (e.g., in HadGEM3-GC3.1, Mackie et al., 2020). Not all models can handle the resulting change in ocean volume, and so a commonly used alternative is to represent a positive freshwater flux as a negative, virtual salinity flux (e.g., in NorESM2, Muilwijk et al., 2026). This implies that no changes in mass or volume are implemented (Jackson et al., 2023). To maximise the number of models that can implement either option, the specified additional freshwater (or virtual salinity) flux should be applied in the surface layer, as an anomaly, i.e., in addition to whatever freshwater fluxes are already sent from the ice sheets to ocean in the pre-industrial control simulation. We acknowledge, however, that surface-only freshwater additions may not be ideal as surface melt of grounded ice may exit ice shelf cavities some hundreds of metres below the surface (Loose et al., 2009; Arnscheidt et al., 2021; Zheng et al., 2021; Hirano et al., 2023)

For Experiments A, B, and C, the hosing is applied off the coast of Antarctica, as illustrated for the NorESM2-LM native grid in Figure 4. Consistent with Swingedouw et al. (2026), the hosing field is defined as:

$$h(j, i) = \begin{cases} \alpha \exp\left(-\frac{r}{r_{\max}}\right), & r \leq r_{\max}, \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where  $r$  is the distance to the coast, with a maximal distance of  $r_{\max} = 300$  km, and  $\alpha$  the scaled hosing rate in units of  $\text{m s}^{-1}$  such that  $\iint h(j, i) dA$  is the total hosing  $H$  in units of  $\text{m}^3 \text{s}^{-1}$ . The hosing fields are homogenous over the year, i.e., no seasonal cycle is implemented in the freshwater fluxes. Further, consistent with Swingedouw et al. (2026), no salinity compensation to minimize drift in global mean salinity is applied.

In future warming scenarios, increasing melt runoff from Greenland is most likely driven by surface melting (Bonsoms et al., 2026). In Antarctica, ice shelf basal melting is likely to dominate at first, with surface melt catching up as ice shelves become less extensive (Coulon et al., 2024). Latent heat for additional surface and ice shelf basal melting is supplied by the atmosphere and ocean, respectively. For the purposes of simplicity, and for consistency with SOFIA tiers 1 and 2 (Swart et al., 2023), we ignore this effect and propose that no additional latent heat fluxes should be implemented. However, we acknowledge that the latent heat flux can be an important component of the heat budget e.g. in the coastal Southern Ocean (Moorman et al., 2026), and we encourage participants to evaluate the related impacts further by following the SOFIA tier 3 *antwater-lh* experiment (Swart et al., 2023).

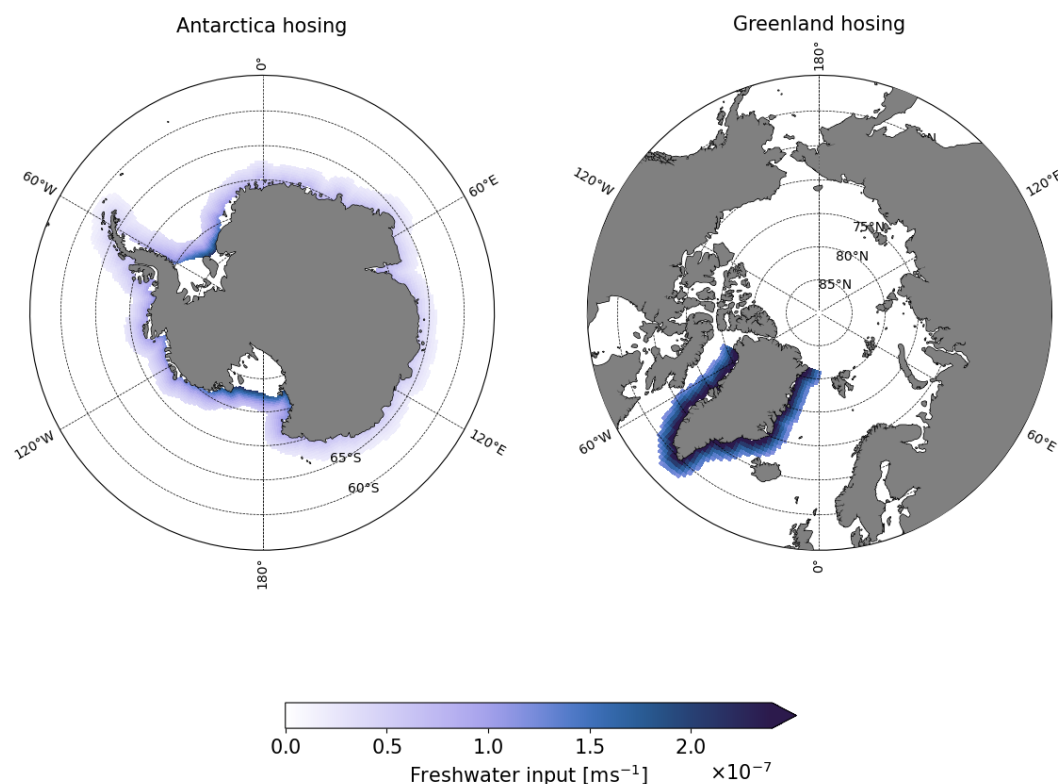


**Figure 4.** Schematic of the freshwater fluxes that are applied in the Southern Ocean around the coasts of Antarctica (left panel) and Greenland (right panel, same spatial mask to apply idealized freshwater perturbations used in the NAHosMIP (Jackson et al., 2023) and TIPMIP-OCEAN (Swingedouw et al., 2026) that was based on the CORE3 protocol (Gerdes et al., 2006)). Fluxes expressed in  $\text{ms}^{-1}$  decrease exponentially with increasing distance from the coast, and are set to zero beyond 300 km (Eq. 1). The total hosing rate  $H$  for either panel is 0.3 Sv, with a total maximum freshwater flux of 0.6 Sv (0.3 Sv from each ice sheet) for the B-experiments.

## 2.4 Model specifications and diagnostics

We propose that the experiments are included in the Coupled Model Intercomparison Project Phase 7 (CMIP7), but the proposed experiments can be run by any emission-driven ESM. We invite participation from as many modelling centres as possible. All simulations within the proposed protocol are emission-driven.

295 The data request follows both that of TIPMIP-ESM (Jones et al., 2026) and TIPMIP-OCEAN phase 1 (Swingedouw et al., 2026) and is publicly available (see code and data section). We further request a subset of additional variables specified in Table 1 that - if available - allow us to assess all surface ocean freshwater components. No sub-daily data are required. We encourage the modelling centres to provide model output following the climate model output rewriter (CMOR) requirements and to submit model outputs to the Earth System Grid Federation (ESGF) portal.



**Table 1.** Data request for surface ocean freshwater flux components in addition to Licon-Salaiz (2025).

| CMIP6 compound name | CMIP7 compound name                    | Physical parameter                                      | Units      |
|---------------------|----------------------------------------|---------------------------------------------------------|------------|
| Omon.prra           | ocean.prra.tavg-u-hxy-ifs.mon.glb      | Rainfall Flux where Ice Free Ocean over Sea             | kg m-2 s-1 |
| Omon.prsn           | ocean.prsn.tavg-u-hxy-ifs.mon.glb      | Snowfall Flux where Ice Free Ocean over Sea             | kg m-2 s-1 |
| Omon.evs            | ocean.evpsbl.tavg-u-hxy-ifs.mon.glb    | Water Evaporation Flux Where Ice Free Ocean over Sea    | kg m-2 s-1 |
| Omon.friver         | ocean.friver.tavg-u-hxy-sea.mon.glb    | Water Flux into Sea Water from Rivers                   | kg m-2 s-1 |
| Omon.ficeberg       | ocean.ficeberg.tavg-ol-hxy-sea.mon.glb | Water Flux into Sea Water from Icebergs                 | kg m-2 s-1 |
| Omon.fsitherm       | ocean.siflfwbot.tavg-u-hxy-sea.mon.glb | Water Flux into Sea Water Due to Sea Ice Thermodynamics | kg m-2 s-1 |

300 **2.5 File naming conventions**

The naming conventions for file submissions to TIPMIP-OCEAN phase 2 for the CMOR format follows the general naming conventions from TIPMIP. This assumes a prefix 'tip-ocn' to refer to the ocean domain if run under CMIP7, and 'tipmip-ocn' if run under CMIP6+. All experiments in this paper are phase 2. Tier 1 assigns mandatory experiments, while lower tier experiments are optional. The naming conventions follow this recipe:

305

CMIP7: tip-ocn-p2t<tier>-<exp-id> or

CMIP6+: tipmip-ocn-p2t<tier>-<exp-id>

310

where ocn refers to the domain, i.e., TIPMIP-OCEAN; p refers to the TIPMIP phase, which for these experiments is 2; <tier> refers to tier 1 or lower; and <exp-id> identifies the individual experiment (see Table 2). The <exp-id> is either A (Southern Ocean hosing) or B (dual-hemispheric hosing) or C (baseline step function) for the experiment group and a letter (a-d) for the sub experiment. The respective official labels for each sub experiment are listed in Table 1.



**Table 2.** Summary of proposed tier 1 experiments A (Southern Ocean hosing) and B (dual-hemispheric hosing in both hemispheres around Greenland and in the Southern Ocean). Tier 2 experiments A and B are the same as tier 1 A[a-d] and B[a-d] experiments, but with a smaller freshwater forcing of 0.1Sv. Experiment C (baseline step function) is tier 2. Adapted from Swingedouw et al. (2020).

| <b>Experiment</b>  | <b>Experiment Aa</b>                                                                                                                                     | <b>Experiment Ab</b>                                                                 | <b>Experiment Ac</b>                                                                                                                                    | <b>Experiment Ad</b>                                                     |
|--------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Label (CMIP7)      | tip-ocn-p2t1-Aa                                                                                                                                          | tip-ocn-p2t1-Ab                                                                      | tip-ocn-p2t1-Ac                                                                                                                                         | tip-ocn-p2t1-Ad                                                          |
| Label (CMIP6+)     | tipmip-ocn-p2t1-Aa                                                                                                                                       | tipmip-ocn-p2t1-Ab                                                                   | tipmip-ocn-p2t1-Ac                                                                                                                                      | tipmip-ocn-p2t1-Ad                                                       |
| Freshwater forcing | Ramp-up in the Southern Ocean                                                                                                                            | Constant in the Southern Ocean                                                       | Ramp-down in the Southern Ocean                                                                                                                         | No freshwater release                                                    |
| Description        | Ramp up run with constant CO <sub>2</sub> emissions leading to a warming of 2°C/century with increasing freshwater release from 0 to 0.3 Sv in 100 years | Zero emission run starting directly after Aa, with freshwater release kept at 0.3 Sv | Ramp down with negative CO <sub>2</sub> emissions leading to a cooling of 2°C/century with decreasing freshwater release from 0.3 to 0Sv over 100 years | Zero emission run starting directly after Ac, with no freshwater release |
| Length             | 100±n years                                                                                                                                              | 250 years                                                                            | 100±m years                                                                                                                                             | 100 years                                                                |
| Initial conditions | Restarts from pi-esm                                                                                                                                     | Restarts from the final year of experiment Aa                                        | Restarts from year 50 of Ab                                                                                                                             | Restarts from final year experiment Ac                                   |
| <b>Experiment</b>  | <b>Experiment Ba</b>                                                                                                                                     | <b>Experiment Bb</b>                                                                 | <b>Experiment Bc</b>                                                                                                                                    | <b>Experiment Bd</b>                                                     |
| Label (CMIP7)      | tip-ocn-p2t1-Ba                                                                                                                                          | tip-ocn-p2t1-Bb                                                                      | tip-ocn-p2t1-Bc                                                                                                                                         | tip-ocn-p2t1-Bd                                                          |
| Label (CMIP6+)     | tipmip-ocn-p2t1-Ba                                                                                                                                       | tipmip-ocn-p2t1-Bb                                                                   | tipmip-ocn-p2t1-Bc                                                                                                                                      | tipmip-ocn-p2t1-Bd                                                       |
| Freshwater forcing | Ramp-up in the Southern Ocean and around Greenland                                                                                                       | Constant in the Southern Ocean and around Greenland                                  | Ramp-down in the Southern Ocean and around Greenland                                                                                                    | No freshwater release                                                    |
| Description        | Ramp up run with constant CO <sub>2</sub> emissions leading to a warming of 2°C/century with increasing freshwater release from 0 to 0.3 Sv in 100 years | Zero emission run starting directly after Ba, with freshwater release kept at 0.3 Sv | Ramp down with negative CO <sub>2</sub> emissions leading to a cooling of 2°C/century with decreasing freshwater release from 0.3 to 0Sv over 100 years | Zero emission run starting directly after Bc, with no freshwater release |
| Length             | 100±n years                                                                                                                                              | 250 years                                                                            | 100±m years                                                                                                                                             | 100 years                                                                |
| Initial conditions | Restarts from pi-esm                                                                                                                                     | Restarts from the final year of experiment Ba                                        | Restarts from year 50 of Bb                                                                                                                             | Restarts from final year experiment Bc                                   |

*Continued on next page*



*Continued from previous page*

| Experiment         | Experiment Ca                                                                             |
|--------------------|-------------------------------------------------------------------------------------------|
| Label (CMIP7)      | tip-ocn-p2t2-Ca                                                                           |
| Label (CMIP6+)     | tipmip-ocn-p2t2-Ca                                                                        |
| Freshwater forcing | Constant in the Southern Ocean                                                            |
| Description        | Baseline step function with a constant freshwater release of 0.1 Sv in the Southern Ocean |
| Length             | 100 years                                                                                 |
| Initial conditions | Restarts from pi-esm                                                                      |

### 3 Conclusions

315 How increasing Antarctic meltwater drives abyssal overturning, as well as its cascading effects on large scale circulation, ocean biogeochemistry and global climate, remains to be fully understood, despite its potentially critical role in modulating Earth's climate (Meniel et al., 2026). Adding to this uncertainty are potential interhemispheric interactions between simultaneous freshening around both Greenland and Antarctica. Illustrating such interhemispheric coupling, reduced Antarctic Bottom Water formation may transiently stabilize the AMOC against an increase in Greenland ice sheet meltwater runoff (e.g., Sinet et al., 320 2025). This highlights the need for a systematic assessment of the coupled dynamics of the SOAC and AMOC under idealised freshwater forcing experiments.

Here, we have introduced the second phase of TIPMIP-OCEAN with several freshwater hosing simulations that are complementary to the North Atlantic hosing experiments described in Swingedouw et al. (2026) and Southern Ocean hosing experiments proposed in SOFIA (Swart et al., 2023), and consistent with the ramp-up, stabilisation, ramp-down framework of 325 TIPMIP (Jones et al., 2026). Beyond the objectives raised within the SOFIA community and TIPMIP-OCEAN protocol, our main scientific questions that can be addressed with the proposed simulations include:

1. What are the short- and long-term Earth System impacts of freshening in the Southern Ocean under 2°C global warming levels?
2. Does the SOAC exhibit reversibility when freshwater and CO<sub>2</sub> forcing is reversed, and if yes, on what timescales?
- 330 3. How sensitive are climate responses to combined global warming and freshwater forcing in both the North Atlantic and the Southern Ocean?



4. How do idealised freshwater fluxes from one ice sheet influence climate responses to freshwater fluxes from the other?  
Are the climate responses additive, synergistic, or opposing?

The results of the highly idealised experiments will provide new insights into the role that freshwater forcing in the Southern  
335 Ocean plays for regional and global climate, and the complexity of dual hemispheric freshwater forcing.

*Code and data availability.* The diagnostic request for the TIPMIP ESM and OCEAN phase 1 experiments is available at  
<https://doi.org/10.5281/zenodo.15189530> (Licon-Salaiz, 2025). An example script for computing the mask file for the freshwater flux around  
Antarctica for the NorESM2-LM native grid can be retrieved at [https://github.com/ffroeb/Tipmip-OCEAN-experimental-protocol-phase-](https://github.com/ffroeb/Tipmip-OCEAN-experimental-protocol-phase-2)  
2 so that each group can recalculate the mask file using their own native grid. The protocol for SOFIAMIP in CMIP7 is outlined at  
340 <https://sofiamp.github.io/cmip7-sofiamp.html>.

*Author contributions.* FF, TT, DC, AR, TM, MB designed the experiments, FF and DC prepared the manuscript with contributions from all  
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