



# TIPMIP-OCEAN experimental protocol phase 1: Tipping dynamics of the AMOC

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**Abstract.** This paper describes the experimental protocol for a set of coordinated simulations involving oceanic surface freshwater flux perturbations, conducted as part of the international Tipping Points Modelling Intercomparison Project (TIPMIP). These simulations constitute the first phase of the TIPMIP-OCEAN domain. We propose this protocol for inclusion in the Coupled Model Intercomparison Project Phase 7 (CMIP7), although it can also be implemented within CMIP6+ or other types of coupled or ocean standalone models. This initial phase focuses primarily on the dynamics of the North Atlantic Ocean, particularly the Atlantic Meridional Overturning Circulation (AMOC). The different experiments are designed to (i) evaluate the impacts of a potential major AMOC weakening under a 2°C global warming scenario, (ii) assess the sensitivity of the AMOC to combined global warming and freshwater forcing, (iii) investigate the potential recovery of the AMOC following the reversal of forcings, and (iv) compare past AMOC variations with available climate observations and reconstructions. Four categories of experiments are included. Experiment group A examines the effect of freshwater release around Greenland under ramp-up, stabilization, and ramp-down scenarios in both CO<sub>2</sub> emissions and freshwater input. Experiment group B complements this idealized set by using historical climate simulations and projections for 1850–2100, incorporating realistic estimates of Greenland Ice Sheet melt based on observations for the historical period and ice-sheet model projections for the future. Experiment group C extends the existing North Atlantic Hosing Model Intercomparison Project (NAHosMIP) by applying large freshwater perturbations to both control and 2°C-warming simulations to assess how global warming influences AMOC reversibility. Finally, experiment group D imposes freshwater inputs, consistent with those inferred for the 8.2 kyr before present event, under pre-industrial conditions, in order to constrain model sensitivity to freshwater forcing using paleoclimate reconstructions. Together, these coordinated experiments will allow systematic evaluation of how different climate models respond to identical freshwater perturbations—an essential step toward better understanding the wide inter-model spread in North Atlantic dynamics and projected future AMOC changes.

## 1 Introduction

On-going climate change is impacting Earth system dynamics and raises the risk of crossing a number of tipping points in various sub-systems (Lenton et al., 2008). An Earth system tipping point is the level (threshold) in the forcing where a large-scale component transitions from one stable state to another. This often happens abruptly (faster than the typical timescale of the system), and the changes may be irreversible on timescales of human interest (i.e. decades to centuries), that is the system does not return to its original state after the change in forcing is reversed to below the threshold (Winkelmann et al., 2025). Despite advances in our understanding of tipping point dynamics (Armstrong McKay et al., 2022), large uncertainties still exist regarding important tipping point features. For example, the exact thresholds are poorly known, particularly in the ocean.



75 The same is true concerning the potential for reversibility. It is therefore crucial to improve our knowledge of the sensitivity of the ocean, especially in regard to future climate change.

The AMOC is a large-scale ocean circulation system, characterized by northward-flowing warm and salty upper-ocean waters and deeper southward-flowing cold and fresh western boundary currents and interior flows below about 1000 m (e.g., Buckley and Marshall 2016). This circulation therefore connects the upper-ocean waters and the deeper ones, through  
80 the formation and sinking of dense deep-water masses mainly formed in the Labrador, Irminger, and Nordic seas, and the upwelling of this deep water primarily in the Southern Ocean and the Indo-Pacific basin (Baker et al., 2023). The Atlantic northward upper limb of the AMOC transports heat northward across all latitudes, peaking around 26°N with a transport of about 1 PW, and is a critical modulator of the regional and global climates. As such, changes in the AMOC, like a weakening, could induce widespread climate impacts stretching from the tropics to the high latitudes (Jackson et al., 2015; Liu et al., 2017),  
85 pushing the climatological equator further to the south (Buckley and Marshall 2016). In particular, a large weakening of the AMOC can cause a cooling in the Northern Hemisphere, especially around the subpolar North Atlantic region, a southward shift of tropical precipitations, severe reductions in summer precipitation over Northern and Western Europe, an increase in European winter storms, higher sea levels at the North Atlantic coastlines, and weakening of the Asian Monsoon, especially over India (e.g., Ben-Yami et al. 2024). The AMOC can also influence the nutrient supply in the North Atlantic (Lynch-  
90 Stieglitz et al., 2024) by modulating the convection and upwelling as well as the horizontal transports, impacting regional, oceanic food chains (Boot et al., 2025). Finally, the AMOC also contributes to the deep sequestration of anthropogenic carbon in the ocean (Perez et al. 2013, Gruber et al. 2019, Boot et al 2025). Many other impacts of an AMOC substantial weakening have been listed in the Special Report on the Ocean and Cryosphere in a Changing climate (SROCC, IPCC 2019, their Fig. 6.10).

95 Reconstructions of past climates have revealed the occurrence of large climatic changes on timescales of decades to millennia, most notably in the North Atlantic (Dansgaard et al., 1982; Heinrich, 1988; Oeschger et al., 1984). Those variations are believed to be mainly related to AMOC changes (Rahmstorf, 2002). Approximately 8200 yrs ago, during the Holocene, a large freshwater outburst from the North American glacial lakes was released into the North Atlantic, temporarily disrupting the AMOC (Alley et al., 2003; Barber et al., 1999; Clarke et al., 2004). Although paleo-proxy data suggest that the freshwater  
100 input was substantial in this event, the resulting cooling persisted for only about a century, implying that the AMOC did not exceed a stability threshold during this event (Gregoire and Morrill 2021).

Theoretical and early modelling studies indicated the existence of multiple AMOC stable states: an “on state”, similar to present-day conditions, and an “off state” with dramatically reduced volume and heat transports (e.g., Stommel 1961; Manabe and Stouffer 1988). In his conceptual model, Stommel (1961) showed that the AMOC can exhibit a strongly non-  
105 linear behaviour with a threshold in freshwater forcing in the North Atlantic, beyond which the AMOC can shift to an “off state”. Reversing this forcing does not automatically lead to a recovery of the AMOC to an “on state”, but with significant delay in both temporal and phase spaces, suggesting the possibility that multiple equilibria are possible under the same forcing conditions. This is known as hysteresis, and is found across a hierarchy of models from simple box models (Dijkstra 2024) to



110 Earth System Models of Intermediate Complexity (EMICs, e.g. Rahmstorf et al. 2005), and fully coupled models participating in Coupled Model Intercomparison Projects (CMIP, e.g. Hu et al. 2012; van Westen et al. 2024; Mecking et al. 2016).

The consequences of these disturbances may persist for a few centuries and even be irreversible on long time scales, a characteristic that corresponds to tipping point behaviour (Lenton et al., 2008). Hence, the AMOC is considered as one of the elements of the climate system components which could undergo tipping behaviour (Swingedouw et al. 2020) and may also be a trigger for other tipping events (known as tipping cascades, Wunderling et al. 2024).

115 Given the potential for the AMOC to switch between “on” and “off” states, it is crucial to better understand its current conditions, its possible future evolution, and the conditions for which the AMOC might transition from an “on” to an “off” state. In response to anthropogenic emission of greenhouse gases, several generations of climate models consistently project a weakening of the AMOC over the 21<sup>st</sup> century, although the rate of weakening varies widely across the models (e.g., Weijer et al. 2020; IPCC 2021). This weakening is mainly driven by surface warming, and freshening of the subpolar North Atlantic  
120 notably due to increases in precipitation and runoff, which are consequences of elevated greenhouse gases. Those changes reduce seawater density, and suppress deep convection and deep-water formation in the North Atlantic. Despite this, the most recent report from the Intergovernmental Panel on Climate Change assessed that “there is medium confidence that there will not be an abrupt collapse before 2100” (IPCC 2021), meaning that this could not be ruled out completely, with the source of uncertainty being due to substantial biases in CMIP-class models. Since then, new analyses have highlighted that some CMIP6  
125 models, within different emission scenarios (even intermediate scenarios), do simulate an AMOC that continues to weaken after 2100 to a very weak state ( $< 6 \text{ Sv}$ ,  $1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$ , e.g., Romanou et al. 2023; Drijfhout et al. 2025) with indications that a tipping point may have been crossed.

One concern that has been raised is that the AMOC in a number of climate models may be overly stable because of biases in the mean state that can affect the key feedbacks governing its stability, tipping behaviour, and recovery (Mecking et al., 2017; Weaver et al., 2012). Particularly important among the stability-governing processes is the salt-advective feedback at the large scale (Rahmstorf 1996). If the AMOC imports (exports) salt in the Atlantic at 34°S (entrance of the Atlantic), a weakening of the AMOC leads to a freshening (salinification) of the Atlantic, resulting in a reduction (increase) in density and an enhanced (reduced) weakening of the AMOC, respectively, i.e., a positive (negative) feedback. Several studies have suggested that the sign of this salt-advective feedback is important for the presence of an AMOC tipping point, and that many  
135 climate models have this feedback negative, while observation-based estimates suggest it is in the phase of a positive (Liu et al., 2017; Mecking et al., 2017; de Vries and Weber, 2005; van Westen and Dijkstra, 2024). On the other hand, some studies have found that the salt-advection feedback may not behave in the same way in complex climate models as in simple box models, and may only be relevant on longer timescales (greater than a century, e.g. Sgubin et al. 2015) or that the feedback might be more relevant is the salt advection entering directly into the subpolar North Atlantic (Cheng et al., 2018). Other  
140 studies suggest that the salt-advection feedback may not be the only important feedback (Rind et al., 2018; Sgubin et al., 2015) and that other processes, such as extreme variability in sea ice processes and high latitude feedbacks, may play a role in destabilizing the AMOC locally (Meccia et al. 2023; Swingedouw et al. 2007; Romanou et al. 2023). Another factor that may



increase the AMOC's vulnerability is the inadequate representation of freshwater input from melting glaciers and ice sheets in previous projections simulated with models without interactive ice sheets. Although earlier studies suggested that this effect was small in CMIP-type models (Devilliers et al., 2021, 2024; Lenaerts et al., 2015), high-resolution ocean simulations indicate potentially stronger impacts, depending on where and how freshwater is applied (Brady and Otto-Bliesner, 2011; He et al., 2020).

Freshwater hosing experiments—simulations where an arbitrary amount of freshwater is released in the North Atlantic—are typically used to simulate the impact of the Greenland ice sheet melting, and other ice sheets from paleo time, on the AMOC in coupled general circulation models (CGCMs) without interactive ice-sheets. A recent model intercomparison shows that under the same freshwater flux perturbation, AMOC does not recover (i.e., its strength does not return to its unperturbed strength) after the freshwater flux perturbation is turned off in half of the participating models, highlighting the role of the model structural differences in determining the AMOC stability (Jackson et al., 2023). Such experiments are useful to understand the different internal climate feedbacks which might control the presence of an AMOC tipping point. However, these experiments with prescribed background CO<sub>2</sub> do not account for interaction between the responses to changing atmospheric CO<sub>2</sub> and those due to freshwater forcing, as well as the combined feedbacks of these responses to the Earth radiative balance. Other experiments (e.g., Jones et al. 2019) focus more on the reversibility of AMOC strength when CO<sub>2</sub> gas concentration is ramping up and down gradually (possibly with a stabilisation in between). Former results to this type of protocol have shown a recovery of the AMOC strength following ramp-down, often with an overshoot in AMOC strength (where the AMOC recovers to a temporarily stronger state than initially), though in some cases the AMOC recovery is delayed (Jackson et al. 2014; Sgubin et al. 2015; Schwinger et al. 2022).

Simulated increases in greenhouse gas concentrations lead to model-dependent regional climate responses, which in turn affect ocean surface fluxes (e.g., freshwater and heat fluxes) in different regions (Gregory et al., 2005). This seriously challenges cross-model comparisons of the exact differences of the ocean dynamics in the projections from different models.

Changes in the AMOC projected by climate models may arise from two main sources: differences in the surface perturbations associated with global warming, and differences in the strength of internal AMOC feedbacks. Because both factors might differ among models, it remains difficult to attribute projected AMOC changes unambiguously—whether they primarily reflect varying externally forced perturbations or the amplification of these perturbations through internal AMOC feedback mechanisms. To address this issue, analysing the response of climate models to an identical perturbation provides a useful framework for isolating and quantifying the internal AMOC feedbacks of a given model (Swingedouw et al. 2007). Thus, to better understand the differences in oceanic response to various forcings among climate models, dedicated experiments with the same perturbations to the ocean (e.g., Stouffer et al. 2006; Swingedouw et al. 2013; Jackson et al. 2023) in pre-industrial conditions or with the same level of global warming are needed. Resolving and understanding these differences are likely a crucial step towards reducing uncertainties of the oceanic response within climate projections.

The Tipping Points Modelling Intercomparison Project (TIPMIP; Winkelmann et al. 2025) aims to explore the stability of Earth systems as well as the dynamics that may lead to a tipping event (e.g., Scheffer et al. 2001). These experiments



are organised across multiple domains, which largely correspond to different, major components of the Earth system: ocean, ice-sheets, permafrost, biosphere, and the interactive Earth system. This paper describes the experimental protocol for the Ocean domain, within the first phase of the TIPMIP (Winkelmann et al. 2025), named TIPMIP-OCEAN. Complementing the  
180 TIPMIP-ESM Tier 1 simulations (Jones et al. 2025), TIPMIP-OCEAN, in its first phase, proposes simulations specifically focusing on the stability, abrupt changes, and reversibility of the Atlantic Meridional Overturning Circulation (AMOC) under different background states and include combined CO<sub>2</sub> and freshwater forcing. These dedicated sensitivity experiments of the AMOC are expected to improve our understanding of the AMOC dynamics in a multi-model framework, thereby helping to better quantify the uncertainties in future AMOC projections.

185 To tackle the different AMOC behaviours in models, TIPMIP-OCEAN will facilitate a large up-to-date multi-model ensemble with combined forcing, something that has been largely missing from previous assessments. The TIPMIP-OCEAN experimental protocol was developed to probe the AMOC's evolution in a warming world, and includes experiments which will assess the potential for crossing tipping points due to transient warming as well as additional freshwater releases. In doing so, TIPMIP-OCEAN complements the ongoing work of other domains in TIPMIP by imposing freshwater forcing on top of  
190 the CO<sub>2</sub> pathways from TIPMIP-ESM. In phase 1, TIPMIP-OCEAN is proposing 4 sets of experiments:

- Experiments A examine AMOC reversibility and impacts in the presence of both increased global temperature and freshwater input.
- Experiments B investigate AMOC response to past and future projections that include realistic freshwater input from Greenland ice sheet.
- 195 • Experiments C are idealised scenarios to evaluate how AMOC thresholds vary across models and global warming levels.
- Experiments D use a scenario from paleoclimate to assess model responses to freshwater.

By establishing standardized protocols for ocean dynamics evaluation, TIPMIP-OCEAN phase 1 aims to identify key feedbacks and model dependencies that control AMOC stability and change, and to provide multi-model information about  
200 impacts. These experiments will improve our understanding of how interactions between idealized freshwater release and global warming could influence the AMOC's long-term evolution and potential tipping behaviour.

## 2 Experimental design

### 2.1 General description

The proposed simplified framework of TIPMIP-OCEAN is designed to maximize participation across modelling groups. All  
205 simulations include freshwater release in the subpolar and polar regions of the North Atlantic with some also including background state changes due to CO<sub>2</sub> concentration changes. Freshwater is added into the ocean (hosing), to mimic the impact of e.g., large freshwater release from the ice sheets, or potentially to address biases in net precipitation in future projections

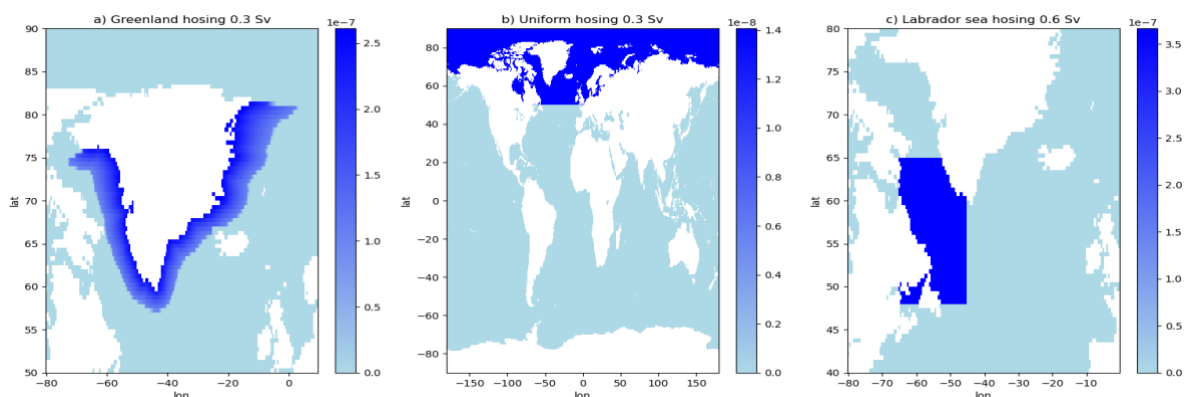


(e.g., Vicente-Serrano et al. 2022). The goal is to represent the impact of increased surface freshening in an idealized context. There are several choices to be made when applying hosing. Although applying hosing through adding freshwater might appear  
210 to be the natural choice, this involves adding mass to the surface which could lead to numerical problems if, for instance, it causes strong gradients in surface height, which models with a rigid-lid approximation cannot handle. Also, some ocean models are unable to represent a mass flux because of approximations to the representation of the ocean surface (Roullet and Madec, 2000). Hence, for consistency among the models' set up, we instead recommend applying the hosing as a virtual salinity flux, meaning that no changes to mass or volume are implemented and instead there is an adjustment to the salinity (Jackson et al.  
215 2023). This allows a consistent protocol that can be followed by all models. Details about applying the hosing can be found in the Appendix A2. However, if this choice is very difficult to implement in some systems, alternative set up for hosing can be applied, but this will be at the expense of a consistent protocol, and is therefore not recommended.

The hosing areas for the proposed experiments are shown in Fig. 1. In experiments A and B, the hosing is applied to a region around Greenland (Fig. 1a). This is the area of meltwater runoff introduction into the ocean (Mankoff et al., 2020).  
220 The implementation protocol can be found in Appendix A1. In experiment C the hosing is applied as a uniform field between 50°N and the Bering Strait (Fig. 1c). This is an idealised protocol to account for the fact that models differ in how well they represent the distribution of freshwater from the boundary currents into the interior, and in the locations in which they form deep waters. Experiment D aims at mimicking the 8.2 kyr event, where large amount of freshwater was released into the Hudson Bay, and flowed into the Labrador Sea (Lewis et al., 2012). Based on the drainage basins of the remnant Ice Sheet  
225 during the end of the deglaciation (Jennings et al., 2015) the hosing region is defined to be in the Labrador Sea (65°W-45°W, 48°N-65°N, see Fig. 1c). For all these regions, the hosing should be applied at the surface for the sake of simplicity. Details of how to calculate and apply the hosing can be found in the Appendix. No seasonal cycle is included here, meaning the freshwater release is homogenous over the year.

Finally, there is a choice of how or whether to compensate the hosing flux with opposing changes in other basins to  
230 prevent drift in the global mean salinity. Such a drift is likely to be small and not dynamically significant when the hosing is not large and not applied for a long period. Also, for more realistic hosing scenarios (e.g., Experiment B), compensation should not be applied. However, for very long idealised experiments, for example when producing hysteresis loops, often a compensation has been applied to prevent drift in salinity. In these experiments, only experiment C uses a compensation to be consistent with the existing experiments run under this protocol (Jackson et al. 2023), but no compensation is applied for the  
235 other experiments (see Appendix A3 for details of applying the compensation). The introduction of a natural flux might cause instabilities in some models and therefore it is left up to the modeling groups whether they will implement a natural or a virtual flux.

The participating models are invited to contribute to any or all of the four (A, B, C, and D) types of experiments but to be considered in the model intercomparison each modelling group must do at least one ensemble member of the Tier 1  
240 experiments. However, a larger ensemble size will better isolate the effects of various forcings from internal variability, which can be large in some models for the AMOC (Bonnet et al. 2021). This will be especially important for experiments B.



245 **Figure 1: Areas of hosing for the proposed experiments: a) hosing around Greenland in experiments A and B (shown as values for 0.3 Sv hosing), b) uniform hosing for experiment C, and c) the Labrador Sea hosing for experiment D (shown as values for 0.6 Sv hosing). Values plotted are freshwater fluxes expressed in m/s. Note the exponential decay of fluxes off the Greenland coast in panel a.**

## 2.2 Model specifications

We invite participation from as wide a range of modelling groups and modelling hierarchies as possible to perform as many experiments. In the first place, this protocol is targeting Earth System Models (ESMs) from CMIP6+ (beyond the 6<sup>th</sup> phase of the CMIP) in order to assess behaviour of latest versions and therefore most comprehensive models including various components of the Earth system. We welcome EMICs, as these models can afford to perform simulations for longer periods, and can also perform hysteresis experiments (Rahmstorf et al. 2025) offering an interesting context to provide to their results of TIPMIP-OCEAN experiments. High-resolution standalone ocean simulations are also desirable since they allow a comparison of high to low resolution ocean features and processes, even though they might miss important feedbacks like atmospheric interactions. Contribution from CGCMs would also be appropriate though they will not include the carbon cycle. Contributions from CMIP5 ESMs and CGCMs are also accepted.

We note that to be included in the TIPMIP-OCEAN Earth System Grid Federation (ESGF) portal, the modeling group must perform the runs as described and the simulation output must be provided following the climate model output rewriter requirements. For those models which cannot do emissions-driven simulations, experiments that require emission scenarios (e.g., experiment A and B) are recommended to follow Jones et al. (2026) for concentration-driven models.

## 2.3 Diagnostics

The data request for TIPMIP-OCEAN follows that of TIPMIP-ESM (Jones et al. 2025) and is available (see code and data section). The list is based on variables from the esm-historical experiment in CMIP6. Sub-daily frequencies are excluded. This data can be used for researching a wide range of scientific topics, and will be useful, for instance, to force offline, domain-specific models in TIPMIP. The protocols from the climate model output rewriter (CMOR) specifically designated for CMIP6+



simulations are to be followed for the diagnostics. When the experiments are performed, all the output data can be deposited on the ESGF nodes.

## 2.4 File naming conventions

This section introduces the naming convention for file submissions to TIPMIP-OCEAN following the CMOR format. The TIPMIP-OCEAN naming follows general conventions from TIPMIP and will assume a prefix code “tipmip-ocn”, referring to the ocean domain. The following information is about the phase and tiers. All experiments in this paper are in phase 1. Each experiment has a designated tier, where Tier 1 assigns the mandatory experiments, and Tier 2 includes additional optional experiments. The modelling groups are welcome to perform any experiment, as long as they provide Tier 1 results for that particular experiment, i.e., a group can select experiment  $Y$  Tier 2 ( $Y \in \{A, B, C, D\}$ ), only if they run the respective Tier 1. Tier 2 characterizes interesting variations for the first experiment, but not all the possible combinations, and additional experiments may be interesting for a specific modelling group.

The naming format for TIPMIP experiments follows the following recipe:

tipmip-`<domain-id>`-p`<phase>`t`<tier>`-`<exp-id>`

where: `<domain-id>` for TIPMIP-OCEAN is ocn; `<phase>` refers to the TIPMIP phase, which for these experiments is 1; `<tier>` refers to tier 1 or 2 given to individual experiments; and `<exp-id>` is an identification of up to 3 characters referring to the individual experiments (see Tables 1-4). For TIPMIP-OCEAN the `<exp-id>` is made up of a letter (A-D) for the experiment group and a letter (a-d) for the sub experiment. As an example, for experiment Aa listed in Table 1, the full CMIP experiment name is tipmip-ocn-p1t1-Aa.

## 3 Experiment A: ramp-up, stabilisation, and ramp-down of greenhouse emissions and freshwater release.

Many experiments addressing the possibility and impacts of crossing an AMOC tipping point in a multi-model framework have been carried out so far and typically imposed freshwater perturbations in a preindustrial climate (e.g., Stouffer et al. 2006). However, such experiments do not fully address the likelihood and climatic impacts of a substantial AMOC weakening in the present or future climate. There have been a few studies which have examined the climatic impact of an AMOC weakening in a global warming scenario (Swingedouw et al. 2007; van Westen and Baatsen 2025). However, these have been conducted with individual models and different experimental designs. To assess the robustness of the simulated impacts, a multi-model study with a common protocol is necessary.

The combined effects of both warming and freshening on AMOC stability have been hardly investigated. Several studies have examined the AMOC response to ramp-up and ramp-down of greenhouse gas emissions, with results showing that the AMOC recovers when greenhouse gas forcing declines, although this recovery may be delayed or have an overshoot (Sgubin et al. 2014, Schwinger et al. 2022). Some models show that the AMOC could recover, even without reducing the



forcing (Bonan et al., 2022). However, these studies have not considered a scenario where there are also additional changes in freshwater input, such as from a melting ice sheet, or warming-induced increased precipitation.

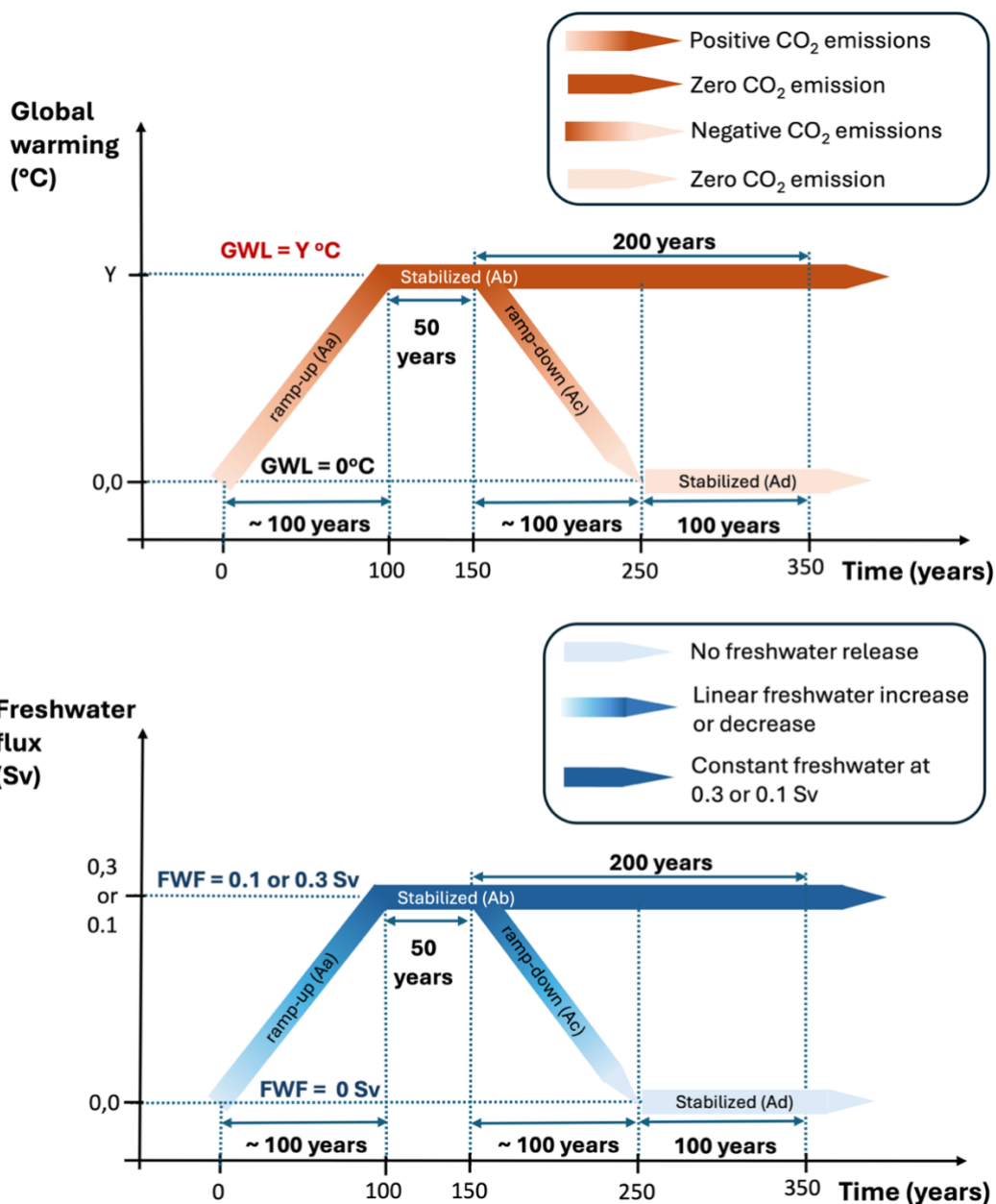
Experiments in the TIPMIP-ESM protocol (Jones et al. 2026) include a ramp-up, stabilisation, and ramp-down scenarios of global mean temperatures to different global warming levels. To complement these experiments, we propose experiments that include the effects of both warming and local input of freshwater. The tier 1 experiments use a large (0.3 Sv) freshwater input to create a strong AMOC weakening. This aims to assess the impacts of a strong AMOC weakening in a warmer climate and to assess the reversibility of an AMOC weakening. The tier 2 experiment uses a smaller hosing input (0.1 Sv) to assess sensitivity of results to a more realistic scenario.

The first experiments are based on the sister experiments from TIPMIP-ESM tier 1 (Jones et al. 2026, see their Fig. 1). Those experiments start from pre-industrial conditions. Global mean surface atmospheric temperature (GMSAT) is then increased by 0.2°C/decade for about 100 years until it reaches 2°C global warming (when averaged over 31 years) relative to preindustrial, using either a given atmospheric CO<sub>2</sub> concentration or CO<sub>2</sub> emission pathway that allows such a ramp-up (Jones et al. 2026). From there, CO<sub>2</sub> emissions are stopped or atmospheric CO<sub>2</sub> concentrations are adjusted with the intention of stabilizing global warming eventually at 2°C. After 50 years, the CO<sub>2</sub> emissions become negative (or atmospheric CO<sub>2</sub> concentration is reduced), with the same absolute rate as during the ramp up, to reach the initial preindustrial GMSAT in about 100 years (see Fig 2). TIPMIP-ESM includes additional experiments with different global warming levels of stabilization. However, in the TIPMIP-OCEAN experiments, we only use the 2°C level, since with higher temperature levels, the freshwater impact on the AMOC might be obscured by the large warming effect from high levels of CO<sub>2</sub> concentration on AMOC (Swingedouw et al. 2015).

The first simulation from the TIPMIP-ESM protocol constitutes the set of control of the TIPMIP-OCEAN experiments A. These sensitivity experiments consist of testing the sensitivity of the North Atlantic to an additional freshwater input, but they also force a strong weakening of the AMOC. It should be emphasized that it is necessary for all modeling groups participating in TIPMIP-OCEAN to perform the equivalent baseline experiment from the TIPESM protocol (Jones et al. 2026). Since the ramp-up from TIPMIP-ESM might not be exactly 100 years, the hosing increment must be modified accordingly. The TIPMIP-ESM ramp-up can actually be longer (or shorter) than 100 years because in the TIPMIP-ESM protocol, the start date of the zero-emission run is defined by comparing a 31-year (centered) mean GMSAT, for each year of the ramp-up, to the 31-year mean GMSAT centered on the same year in the `esm_piControl` from which the ramp-up started (cf. TIPMIP-ESM protocol from Jones et al. 2026). Thus, within TIPMIP-ESM, the ramp-up phase may take “n” years more or less than 100 years, where n is an integer and is likely to be positive, but could also be negative in some model simulations. We propose to strictly follow the TIPMIP-ESM trajectory, to have comparable experiments. This means that, for example, if the ramp-up is taking 100+n years in TIPMIP-ESM simulations, then the ramp-up hosing should also take 100+n years, adjusting the increments of freshwater release by 0.3/(100+n) Sv (0.1/(100+n) for tier 2), with increasing CO<sub>2</sub> following what is done in TIPMIP-ESM. The same should also be applied for the ramp-down, following the same length as the TIPMIP-ESM experiments and adjusting the freshwater release increments.



- 330 In summary, Experiment A consists of different sub-experiments that are depicted in Fig. 2:
1. A CO<sub>2</sub> ramp-up starts from a pre-industrial simulation and runs for around ~100 years at + $X$  GtC/yr, using exactly the same rate  $X$  of CO<sub>2</sub> emission from the TIPMIP-ESM protocol (Jones et al. 2026). The novelty here is to also add a prescribed freshwater flux that increases from 0 Sv at year=1 to +0.3 Sv (or 0.1 Sv) at year ~100, the very same year as defined to start the global warming stabilization run in TIPMIP-ESM.
  - 335 2. A zero-emission run branches off run (1) when GMSAT reaches 2°C in TIPMIP-ESM and  $Y$ °C in the ramp-up hosing experiments (potentially different due to interactions with hosing). It starts at the exact same year chosen to start the stabilisation run in TIPMIP-ESM. The TIPMIP-OCEAN run also retains the +0.3 Sv or 0.1 Sv of freshwater flux and runs for 250 years.
  3. After 50 years of run (2), emissions are set to  $-X$  GtC/yr to ramp-down towards the pre-industrial conditions and this
  - 340 4. At year = ~100 of run (3) (when GMSAT reaches preindustrial GMSAT in TIPMIP-ESM when averaged over 31 years), emissions are set to zero, freshwater flux is also zero, and the run is extended for 100 years with external forcings equivalent to a pre-industrial run.



345 Figure 2: Representation of the protocol of experiment A. The CO<sub>2</sub> emission protocol for the 2°C warming experiments from TIPMIP-ESM constitutes the references. Top panel shows the global warming levels (GWL) that can be reached in the hosing experiments. The GWL after the ramp-up in CO<sub>2</sub> emission (with the same rate  $X$  as used in TIPMIP-ESM) is not necessary 2°C due to interactions between hosing and GWL and is noted  $Y$ . The hosing released around Greenland in the different experiments is shown in the bottom panel. It shows a symmetrical ramp-up and ramp-down of freshwater forcing with the same timing as when the different global warming levels are reached. The global-mean surface air temperature is expressed as an anomaly compared to pre-industrial control simulations in °C, while the freshwater flux is expressed in Sv. Two different forcings can be realized, adding 0.3 Sv (Tier 1) or 0.1 Sv (Tier 2) maximum.

350



355 It is interesting to note that the ~350 years of ramp-up and stabilisation at 0.3 Sv is approximately corresponding to a total freshwater release similar to the total volume of the Greenland ice sheet (Mu et al., 2020). This confirms that this experiment is idealized – since the Greenland ice sheet is unlikely to melt so rapidly especially with a 2°C warming – and mainly aims to estimate the impact of an AMOC weakening in a warming world among different models and to assess potential reversibility

360 If the global warming is not 2°C at the end of the TIPMIP-OCEAN ramp-up due to the introduction of freshwater, the emission rate or the length of simulation should not be adjusted, but strictly follow the one from TIPMIP-ESM. Indeed, due to AMOC weakening which itself could impact the GMSAT, it is likely that the TIPMIP-OCEAN ramp-up experiment with freshwater release will not reach exactly 2°C warming. This is an impact which will be very interesting to study in a multi-model ensemble.

**Exp A. Global Warming Level and hosing**

<b>Tier 1 Experiment Aa</b>	<b>Tier 1 Experiment Ab</b>	<b>Tier 1 Experiment Ac</b>	<b>Tier 1 Experiment Ad</b>	<b>Tier 2 Experiments A[a-d]</b>
Ramp-up around Greenland	Constant around Greenland	Ramp down around Greenland	No freshwater release	Same as all experiments from tier 1 A but with 0.1 Sv instead of 0.3 Sv.
Ramp up run with increasing 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 decreasing CO <sub>2</sub> emissions leading to a cooling of ~ 2°C/century with decreasing freshwater release from 0.3 to 0 Sv over ~100 years	Zero emission run starting directly after Ac, with no freshwater release	



<b>Length:</b> ~100 years <b>Initial conditions:</b> Restarts from piControl <b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Aa	<b>Length:</b> 250+ years <b>Initial conditions:</b> Restarts from the final year of experiment Aa <b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Ab	<b>Length:</b> ~100 years <b>Initial conditions:</b> Restarts from year 50 of Ab <b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Ac	<b>Length:</b> 100+ years <b>Initial conditions:</b> Restarts from final year experiment Ac <b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Ad	<b>Total Length:</b> 550 years+ <b>Official CMIP7 labeling:</b> tipmip-ocn-plt2-A[a-d]
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365 **Table 1: Summary of the proposed experiments A, their tier, and their name, with a description of their main principle, their length, and initial conditions as well as their official CMIP7 labeling to be used.**

#### 4 Experiment B: Greenland Ice-Sheet Melting

370 Future evolution of the Greenland ice sheet (GrIS) is expected to result in mass loss and an increased freshwater input into the ocean (Payne et al., 2021). However, such a melting is neglected or not fully represented in CMIP6 models (Bakker et al., 2016). The associated additional freshwater release in the ocean would increase stratification, decrease oceanic deep water mass formation and hence potentially weaken the AMOC (Swingedouw et al. 2006). Ideally, the impact of melting ice sheets on the AMOC should be examined by considering ESMs fully coupled with an ice sheet model. However, the development of such fully coupled ESMs is still being pursued by many institutions due to a wide number of technical issues.

375 Furthermore, a number of studies using such fully coupled ESMs indicate that in a high emission scenario, the additional freshwater forcing from the melting of GrIS has little impact on the AMOC compared to a simulation with no Greenland ice sheet melting (Goelzer et al., 2025). However, recent climate models may have an AMOC that is more sensitive to freshwater input than previously observed (Laura C. Jackson et al., 2023). In particular, if the model is very close to a threshold and is sensitive to random perturbations (Oh et al., 2025; Romanou et al., 2023), then the additional freshwater flux may be enough to trigger a more substantial weakening.

380 To account for effects in ESMs not coupled to ice sheet models and their complex dynamic boundary system, a number of studies have imposed a freshwater input around Greenland to represent realistic inputs from melting (Devilliers et al. 2021, 2024). However, the impact of realistic forcing on the AMOC has not been systematically explored in current-generation ESMs and might differ depending on the model considered and the number of ensemble members (Romanou et al., 2023). In experiment B, we propose a design for experiments that introduces freshwater discharges from recently evaluated estimates of historical (Schmidt et al. 2025) and future (Goelzer et al., 2025) GrIS melting. This experiment, therefore, focuses on 385 evaluating how the GrIS melting has and can impact the AMOC in the future (in addition to the global warming effect).



The freshwater input applied in this experiment is derived from estimates of mass loss from the GrIS, a source of freshwater that is not realistically represented in most CMIP6 ESMs. In a few CMIP6 models, freshwater release from the ice sheet is parameterized through simplified treatments of snow accumulation, primarily to ensure global water conservation within the model. As a result, the additional freshwater associated with increased snowfall and an intensified hydrological cycle is already implicitly included in these simulations. However, realistic mass loss from the GrIS—such as that associated with enhanced surface melt and ice discharge—is generally not represented. Consequently, introducing GrIS mass loss as an additional freshwater flux in experiment B partly compensates for this model limitation while maintaining the same model configuration. Although this approach may imperfectly account for potential double counting of runoff, the extent of this issue likely remains model-dependent due to differences in how the hydrological budget is closed across models.

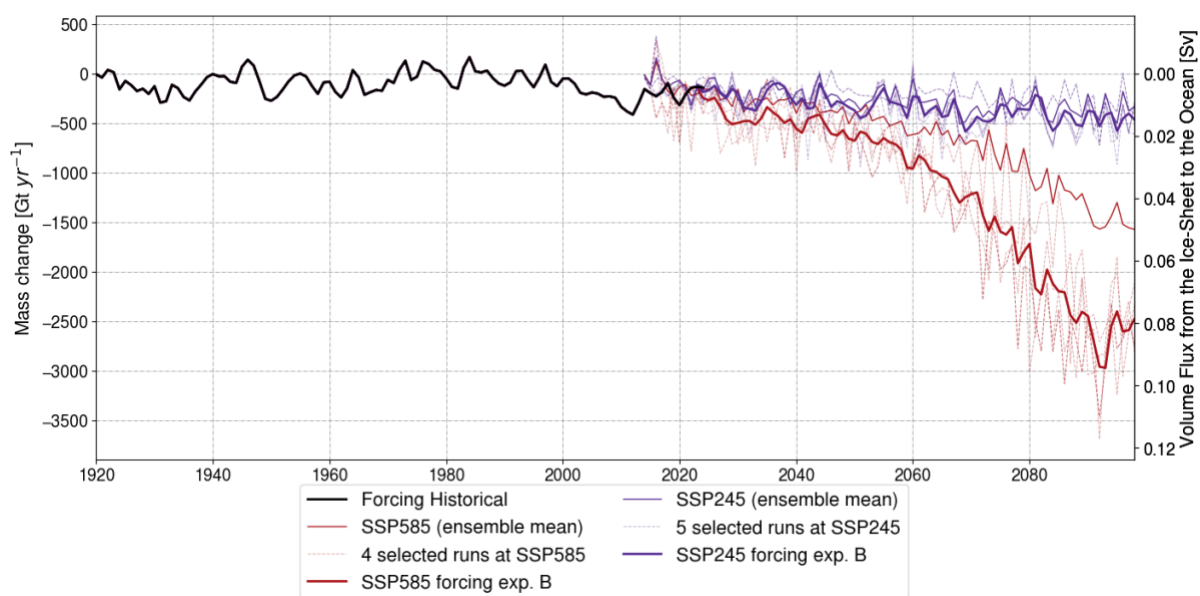
Experiment B will be divided into two specific periods: the historical period and a projection period. The freshwater input during the historical period (Fig. 3) is based on the recent reconstructions for the observed Greenland Ice Sheet mass balance derived from (Schmidt et al. 2025). Projections based on ice sheet models are providing the freshwater inputs for the future period. The efforts for this come from different institutions collaborating to the PROTECT project (Goelzer et al., 2025), which comprised ensembles of ice sheet evolution from different ice sheet model simulations forced following various Shared Socioeconomic Pathways (SSPs) (Gidden et al. 2019). A forcing dataset for GrIS melting has been prepared for these experiments B by merging the latest reconstructed mass balance (Mankoff et al., 2020; Schmidt et al., 2025) over the historical period (until 2024) with mass balance projections (from 2025) extracted from two SSP scenarios (Goelzer et al. 2025). Only the models with high GrIS melting were selected, a list is available in Appendix A4. Tier 1 of experiment B consists of forcing the ESMs using reconstructed (until 2024) and projected (from 2025) simulated GrIS mass loss, included as freshwater release in the ocean, computed using the SSP2-4.5 scenario from 1920 until 2100 (Fig. 3). Tier 2 (optional) uses GrIS mass loss projections following the emission scenario (SSP5-8.5). The freshwater forcing corresponding to GrIS mass loss is chosen to be distributed around Greenland, as shown in Fig. 1a and described in the Appendix. Although it is not as realistic as the one proposed in Schmidt et al. (2025) – following the main ice sheet drainage basins – allows the use of the same pattern as in Experiment A. Also, since we use GrIS mass loss, it is not straightforward how to attribute mass losses to the different main ice sheet drainage basins due to surface accumulation. Some sensitivity tests using the more realistic mask from Schmidt et al. (2025) might be useful to estimate the impact of this simplification. The experiment also neglects latent and sensible heat from meltwater release in the ocean and only considers the direct impact on salinity of the freshwater release. Similar experiments have previously been conducted. Although some impacts have actually been observed in high-resolution models considering a similar methodology (Martin and Biastoch 2023; Swingedouw et al. 2022), the impact of observed Greenland ice sheet melting has been found to be very small in two CMIP6 models (Devilliers et al. 2021, 2024). Hence, we encourage modelling groups to consider running several ensemble members in order to be able to correctly isolate the effect of this small melting over the historical period from the internal AMOC variability found in climate models. Tier 1 will request at least 3 members to better isolate the freshwater release impact from the internal climate variability. A recommendation is to force the ensemble members for the historical period with at least 30 years distance selected from a pre-industrial simulation, which supposed to



be in quasi-equilibrium. The emissions scenarios start from 2014 and modeling centers should follow the CMIP6 protocol (Tebaldi et al., 2021) using SSP2-4.5 for Tier 1 and SSP5-8.5 for Tier 2.

The atmosphere and climate should also evolve during this period, following the same SSP scenario. Since a parallel experiment is required without hosing but with the same SSP scenario, we expect that model groups will use the CMIP6 version of their models, for which these experiments have already been conducted. Institutes are still welcome to submit runs with alternative versions (i.e. CMIP6+/CMIP7), but that requires an additional submission of the SSP-like emissions scenarios without ice sheet melting to be considered as a control run. If model groups do not use the CMIP6 version of their model, they should indicate the specific control version in their submission. All groups should indicate whether ice-sheet coupling or an analogue strategy to obtain freshwater discharges from ice melting was used.

430



435 **Figure 3: Greenland Mass balance and corresponding volume flux in Sv. The historical period uses the reconstructed Greenland Mass balance from Schmidt et al. (2025), as presented in Mankoff et al. (2025). For the projections starting in 2024, the SSP2-4.5 and SSP5-8.5 scenarios are provided by ice sheet model contributors to the PROTECT project (Goelzer et al., 2025). The graph shows the ensemble mean for the multi-model ensemble extending until 2100. For each scenario, the thicker line represents the GRIS melting from projections available to force experiment B, and the thinner dashed lines are the runs selected for their extreme melting, listed in Appendix A4.**

440



## Exp B. Greenland Ice Sheet Melting

Tier 1 Experiment Ba	Tier 1 Experiment Bb	Tier 2 Experiment B[ab]
Historical simulations including reconstructed Greenland Ice Sheet melting	SSP2-4.5 projection including Greenland Ice Sheet Melting, reconstructed over 2015 and 2024 and projected from 2025	SSP5-8.5 projection including Greenland Ice Sheet Melting, reconstructed over 2015 and 2024 and projected from 2025
<b>Length:</b> 95 years covering 1920-2014 with at least 3 members  <b>Official CMIP7 labeling:</b> tipmip-ocn-p1t1-Ba	<b>Length:</b> 86 years covering 2015-2099 with at least 3 members  <b>Official CMIP7 labeling:</b> tipmip-ocn-p1t1-Bb	<b>Length:</b> 85 years covering 2015-2099 with at least 3 members  <b>Official CMIP7 labeling:</b> tipmip-ocn-p1t2-Bb

**Table 2: Summary of the different experiments B, their tier, and their name, with a description of their main principle, their length, and initial conditions as well as their official CMIP7 labeling to be used. Additional simulations varying the initial conditions to compose ensemble members are recommended for each tier.**

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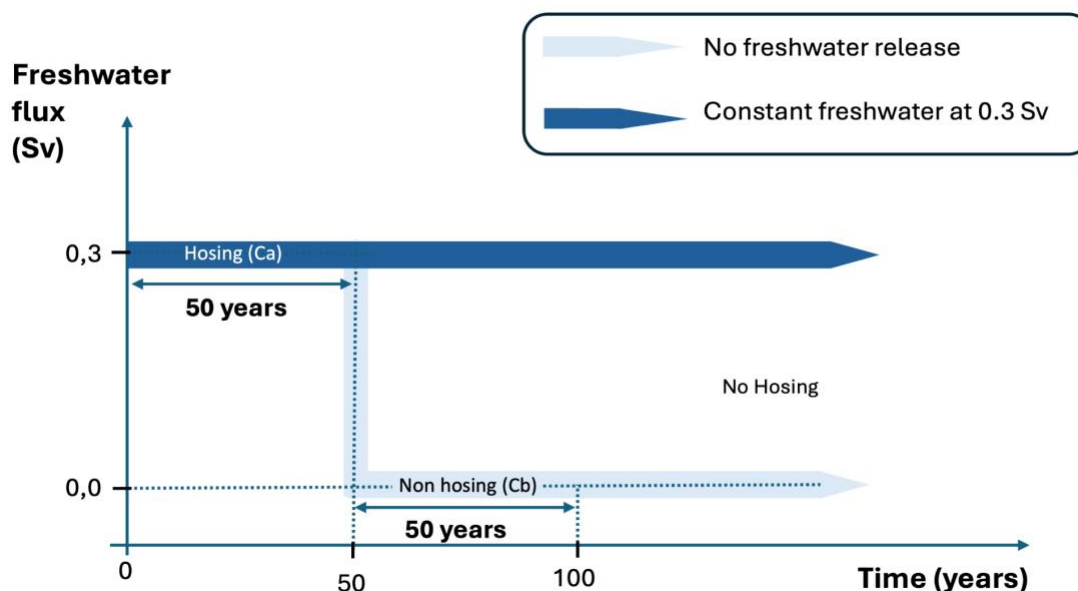
### 5 Experiment C: NAHosMIP update

Although hysteresis experiments have shown the presence of an AMOC tipping point in a range of models, testing this in many complex climate models has proved difficult because of limited computational resources. Applying a freshwater flux for a limited time is a simple, alternative methodology, which can indicate whether a tipping point has been crossed and allow comparison of mechanisms across models. A previous project, the North Atlantic Hosing model intercomparison project (NAHosMIP; Jackson et al. 2023), conducted idealised experiments applying a constant freshwater flux for a fixed time. Results from eight CMIP6-era models found that in half of the participating models, the AMOC did not recover for at least 100 years after it weakened sufficiently through applying hosing (Jackson et al. 2023, Jackson et al 2026). Although

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simulations are not sufficiently long to demonstrate multiple stable equilibria, there is an indication that a threshold has been  
 455 crossed in these models. These are simple, idealised experiments designed to test the reversibility of the AMOC in a number  
 of models, and have the benefit of having already been conducted by several models. Increasing the number of models involved  
 would allow more robust analysis of what controls the presence of the AMOC threshold.



460 **Figure 4: Representation of the protocol of experiment C. The freshwater forcing is expressed in Sv, while the x-axis is in years. The dark blue stands for 0.3 Sv forcing rate and the light blue for no freshwater released. The experiments can be performed under preindustrial conditions (tier 1) or in 2°C global warming conditions (tier 2).**

In this protocol, we use a subset of the NAHosMIP experiments and also include a repetition of these experiments, but in a  
 465 climate that is 2°C warmer than preindustrial simulation. These experiments help to understand how the warmer climate  
 impacts the identified AMOC threshold, and provide data for assessing impacts of an AMOC weakening in a warmer climate.

Tier 1 experiments are initialised from preindustrial conditions and use preindustrial forcings. A hosing of 0.3 Sv is applied uniformly over the region from 50°N in the Atlantic to the Bering Strait (see Fig. 1b) and is compensated throughout the volume of the whole ocean to prevent a drift in salinity (see section 2.1).

470 For tier 1 experiments, the protocol is (cf. Fig. 4):

1. A first experiment (Ca) applies 0.3 Sv hosing at a constant rate for at least 50 years.
2. A second experiment (Cb), which applies no hosing, is then initialised from experiment “Ca” after 50 years of hosing and run for 100 years.



475 For tier 2 experiments, they are the same as tier 1 but with the baseline experiment being a stabilisation at 2°C warmer than preindustrial. This baseline experiment is corresponding to experiment esm-up2p0-gwl2p0, from the TIPMIP-ESM protocol (Jones et al. 2026).

**Exp C. NAHosMIP**

<b>Tier 1 Experiment Ca</b>	<b>Tier 1 Experiment Cb</b>	<b>Tier 2 Experiments C[a,b]</b>
<p>Uniform hosing of 0.3 Sv north of 50°N in North Atlantic to Bering Strait</p> <p>Equivalent to NAHosMIP u03-hos experiments (Jackson et al. 2023)</p>	<p>No hosing initialised from run Ca</p> <p>Equivalent to NAHosMIP u03-r50 experiments (Jackson et al. 2023)</p>	<p>Similar to tier 1 C but applying hosing in a warmer world of around ~2°C. The protocol for the baseline experiment achieving the warmer world is esm-up2p0-gwl2p0 from TIPMIP-ESM (Colin et al. 2025) with Ca being initialised at the same time as the baseline experiment.</p>
<p><b>Length:</b> 50+ years</p> <p><b>Initial conditions:</b> Restarts from piControl</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-p1t1-Ca</p>	<p><b>Length:</b> 100+ years</p> <p><b>Initial conditions:</b> Restarts from year 50 of Ca</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-p1t1-Cb</p>	<p><b>Length:</b> 100+ years</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-p1t2-C</p>

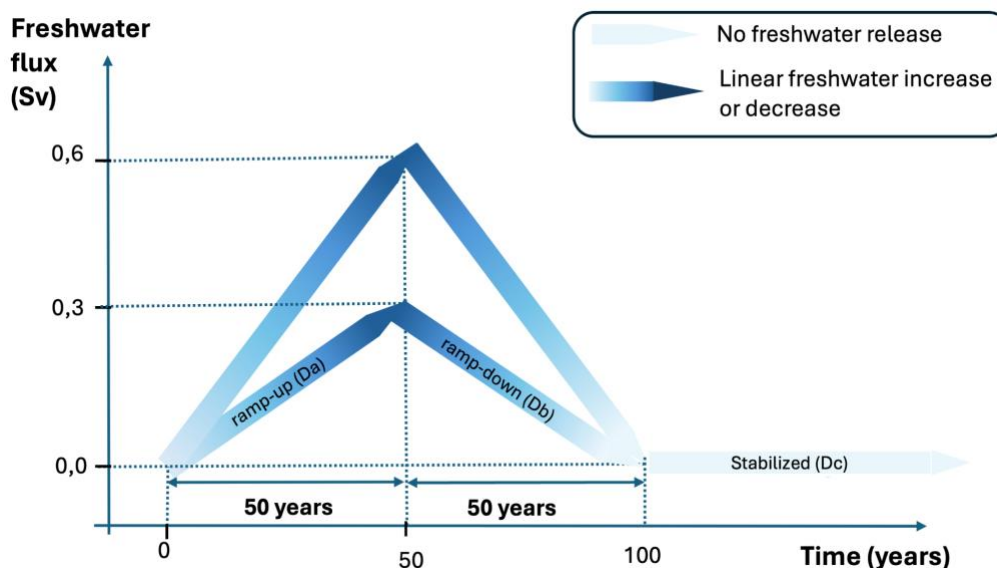
**Table 3: Summary of the proposed experiments C, their tier, and their name, with a description of their main principle, their length, and initial conditions as well as their official CMIP7 labeling to be used.**

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## 6 Experiment D: 8.2 kyr event

Since there are large model uncertainties in the AMOC projections (Weijer et al. 2020), there is a strong need to better assess the sensitivity of the AMOC to freshwater release in the North Atlantic. In this respect, past evidence of large AMOC changes could provide useful test-beds for climate models. There are many abrupt climate change events that could be attributed to significant changes in AMOC during the last glacial period, such as the Heinrich stadials (Hemming 2004; Heinrich 1988) and the Dansgaard-Oeschger events (Dansgaard et al., 1982; Lynch-Stieglitz et al., 2024; Menviel et al., 2020). However, there is only one such event during the present interglacial, i.e., under conditions similar to today. This event occurred about 8,200 years before the present and lasted for about 160 years (Alley et al., 1997; Morrill et al., 2013; Parker and Harrison, 2022) and is often referred to as the 8.2 kyr event. During the glacial period the AMOC might have had a very different sensitivity to freshwater release in the North Atlantic (e.g. Ganopolski and Rahmstorf 2001). Furthermore, the exact rates, locations, or durations of freshwater release for other events during the last glacial period are not well known. In contrast, there exists better evidence concerning the amount of freshwater release for the 8.2 kyr event (Lochte et al., 2019; Matero et al., 2017). It is therefore a good candidate for estimating AMOC sensitivity to freshwater release in an interglacial climate (Schmidt and Legrande 2005). The 8.2 kyr event is characterized by the drainage of glacial lakes Agassiz and Ojibway as well as from the Hudson Bay Ice Saddle, and the freshwater was released along the Hudson Bay and into the Labrador Sea. It is believed to have caused a large weakening of the AMOC (Gregoire and Morrill 2021). This cooled the Northern Hemisphere for an extended period (LeGrande et al., 2006) and generated far reaching global impacts (Morrill et al., 2013).



500 **Figure 5: Representation of the protocol of proposed experiment D.** The freshwater forcing is expressed in Sv, while the x-axis is in years. The freshwater is increasing in ramp-up and decreasing in ramp-down by an increment of 0.006 Sv/year, reaching 0.3 Sv, in tier 1 and 0.012 Sv/year reaching 0.6 Sv in tier 2. The dark blue stands for 0.3 Sv (tier 1) or 0.6 Sv (tier 2) forcing rate and the light blue for no freshwater released.



505 The exact amount of freshwater discharged into the Labrador Sea remains uncertain. Typically, modeling studies for the 8.2 kyr event have used a freshwater flux of 2.5 to 5 Sv for one year corresponding to the very rapid drainage of glacial Lakes Agassiz and Ojibway (e.g., LeGrande and Schmidt 2008, Morrill et al. 2014). With this freshwater flux, models usually do not simulate a large AMOC weakening and poorly resemble proxy evidence from the climatic changes associated with this event. More recently, Matero et al. (2017) tested a range of freshwater rates and duration ramping up from 0 Sv to 0.3 Sv (0.6 Sv in tier 2) 510 in 50 years and ramping down to 0 Sv in another 50 years mimicking the Hudson Bay Ice Saddle collapse thought to have taken place at the time of the 8.2 kyr event. The simulated changes in AMOC, temperature, and precipitation match the paleo proxy data better than those from a sudden lake outburst alone (Du et al., 2025). This freshwater flux is equivalent to a 2.65 m of global mean sea level rise in 100 years, similar to the estimate based on stable isotopes (Aguiar et al., 2021), but a lot higher than the estimate based on the collapse of Lakes Agassiz and Ojibway only (e.g., Rush et al. 2023). As such the total from 515 those two releases might be higher than observed sea level rise. Lochte et al. (2019) estimated, based on assessment of its area extent, that Hudson Bay Ice Saddle could have stored and released about 451,000 km<sup>3</sup>, in agreement with ice sheet modelling results from (Gregoire et al. 2012). Such an estimate would lead to a ramp-up and ramp-down with a maximum of approximately 0.3 Sv, about half the rate used to produce the best matched climate from Matero et al. (2017).

Based on these previous proxy and modelling studies, within the TIPMIP-ocean domain, we propose a coordinated 520 experiment to test the sensitivity of the AMOC to the freshwater forcing of a magnitude similar to 8.2 kyr event under preindustrial conditions. There are a few reasons to do this simulation under preindustrial conditions: (i) this simulation is easy to carry out by many modelling groups without running of a long 8.2 kyr control simulation; (ii) this simulation can be easily compared with other similar simulations from the literature or from TIPMIP-OCEAN. Furthermore, PMIP will possibly consider the same protocol but under 8.2 kyr conditions to allow an identification of the role potentially played by background 525 climatic conditions for the AMOC sensitivity to freshwater release (e.g. Swingedouw et al. 2009)

The freshwater forcing will be added into the Labrador Sea (between 65°W-45°W, 48°N-65°N, see Fig. 1c) as a surface freshwater flux. Two tiers are proposed. In tier 1 experiments, freshwater forcing ramps up linearly from 0 Sv to 0.3 Sv in 50 years and ramps down linearly from 0.3 Sv to 0 Sv in another 50 years (as in Matero et al. 2017), then there is another 100 years with 0 Sv freshwater flux. In tier 2, freshwater ramps up linearly from 0 Sv to 0.6 Sv in 50 years and ramps down 530 linearly from 0.6 Sv to 0 Sv in another 50 years, then there is another 100 years with 0 Sv freshwater flux (Fig. 5).



**Exp D. 8.2kyr event**

<b>Tier 1 Experiment Da</b>	<b>Tier 1 Experiment Db</b>	<b>Tier 1 Experiment Dc</b>	<b>Tier 2 Experiments D[a-c]</b>
<p>Uniform hosing in the Labrador Sea</p> <p>Ramp-up to 0.3 Sv in 50 years (i.e., 6 mSv increment each year), corresponding to the same amount of water as 50 years of NAhosMIP u03hos.</p>	<p>Uniform hosing in the Labrador Sea</p> <p>Ramp-down from 0.3 Sv to 0.0 Sv in 50 years (i.e., -6 mSv increment each year)</p>	<p>No hosing, initialised from run Db.</p>	<p>Same as tier 1 D but reaching 0.6 Sv (i.e., 12 mSv increment each year) in place of 0.3 Sv</p>
<p><b>Length:</b> 50 years</p> <p><b>Initial conditions:</b> Restarts from piControl</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Da</p>	<p><b>Length:</b> 50 years</p> <p><b>Initial conditions:</b> Restarts from last year of experiment Da</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Db</p>	<p><b>Length:</b> 100+ years</p> <p><b>Initial conditions:</b> Restarts from last years of experiment Da</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-plt1-Dc</p>	<p><b>Length:</b> 200+ years</p> <p><b>Official CMIP7 labeling:</b> tipmip-ocn-plt2-D[a-c]</p>

535 **Table 4: Summary of the proposed experiments D, their tier, and their name, with a description of their main principle, their length, and initial conditions as well as their official CMIP7 labeling to be used.**

**7 Priority science questions in TIPMIP-OCEAN**

Given the huge uncertainty concerning the AMOC's fate among models participating in CMIP6, obtaining a better understanding of the cause of this spread is important for reducing uncertainty. To achieve this, dedicated climate model



540 experiments targeting AMOC dynamics are essential for improving our understanding of the AMOC and its response to changes in key forcing factors.

Phase 1 of TIPMIP-OCEAN will therefore allow the community to address key questions concerning the dynamics of the AMOC in response to various forcings mimicking potential past as well as future changes of the climate system. Furthermore, idealized experiments forcing an AMOC weakening will allow the community to better evaluate the impacts of  
545 such an event in a number of realms of the Earth System. Those experiments will also permit the evaluation of the reversibility properties following such a weakening.

Therefore, the main scientific questions that this MIP will be able to address can be summarized as follows:

1. What are the impacts of a potential major AMOC weakening under a 2°C global warming scenario? How do these impacts cascade across physical, biogeochemical and biological systems?
- 550 2. What is the sensitivity of the North Atlantic circulation to combined global warming and freshwater forcing?
3. Is the AMOC reversible on policy-relevant timescales following the reversal of forcings?
4. What can we learn by comparing past simulated AMOC variations with available climate observations and reconstructions?
5. What are the feedback mechanisms controlling the oceanic response? How do these vary across models?

555 A number of other questions relating to climate and ocean dynamics not anticipated here will certainly also emerge from the analysis of those experiments by the scientific community. In this respect, we hope that these experiments will lead to new insights and better estimates of the future of the AMOC that will feed a number of key assessments of the risk of an AMOC tipping, including next IPCC reports.

## 8 Conclusions

560 There is still a lot of uncertainty around the likelihood of crossing an AMOC tipping point in the future. Paleoclimate evidence suggests that the AMOC has crossed a tipping point in the past, leading to persistent climatic shifts. Model projections of the AMOC indicate weakening under greenhouse gas emissions, but the magnitude varies widely, raising questions about its stability under global warming. The uncertainties in the AMOC fate are due to different model sensitivities in response to the increase in greenhouse gases and the lack of ice sheet dynamics in climate projections. This highlights the need for improved  
565 understanding of its dynamics under controlled simulations, focusing on the freshwater budget in the North Atlantic sector, as well as the complex interactions between various components of the climate system and their response to an AMOC weakening.

The protocol for the experiments in the Tipping Point Model Intercomparison Project (TIPMIP) Ocean domain in the first phase addresses some gaps by evaluating AMOC responses to surface freshwater flux perturbations in different sets of  
570 experiments. The goal is to refine AMOC tipping point predictions, feedback mechanisms, and potential impacts of an AMOC



weakening in a warming world. The comparison of responses of different models to the same perturbation will allow insights into model sensitivity and properly assess feedback mechanisms, as well as potential irreversibility of an AMOC weakening.

## Appendices

### A1 Calculating hosing fields

575 For experiments A and B, the hosing field is applied around Greenland (Fig. 1a) with the distribution using the protocol defined by CORE3 (Gerdes et al. 2006). The region it is applied over is around the coast of Greenland from 76°N in the west, southwards around the tip of Greenland and northwards to 81°N in the east. The hosing field is then defined as

$$h(j, i) = \alpha \exp(-r/r_{max}) \quad \text{for } r \leq r_{max} \\ = 0 \quad \text{otherwise}$$

580 where  $r$  is the distance perpendicular to the coast,  $r_{max} = 300$  km and  $\alpha$  is defined such that the spatial integral of  $h$  (in units of  $\text{m}^3 \text{s}^{-1}$ ) is the hosing  $H$  (in units of  $\text{m}^3 \text{s}^{-1}$ ).

For experiment C the hosing is applied from 50°N in the Atlantic, through to the Bering Strait (Fig. 1b), and for experiment D the hosing is applied in the Labrador Sea (65°W-45°W, 48°N-65°N; Fig. 1c). For both these regions, the hosing field  $h$  that is applied at each gridpoint within the region is defined as  $H$  (the total hosing in  $\text{m}^3 \text{s}^{-1}$ ) divided by the area of the region.

### 585 A2 Applying hosing fields

There are several ways in which a freshwater flux can be applied to the ocean. Previous studies have applied the freshwater fluxes as virtual salinity fluxes so that they do not add volume to the ocean. This has avoided issues in models where the ocean used a rigid lid approximation or a linear free surface. Although some models now use a nonlinear free surface, where precipitation adds volume to the ocean, for consistency we use a virtual salinity flux for all models. This virtual salinity flux  $f_s$

590 is defined as

$$f_s(t, j, i) = - \frac{h(j, i) S_0(t, j, i)}{dz_0(j, i)}$$

where  $h$  is the local freshwater flux in units  $\text{m} \text{s}^{-1}$  and  $dz_0$  is the top-layer thickness (Roulet and Madec 2000).  $S_0$  (PSU) is the salinity used in each model to translate surface freshwater fluxes to salinity changes. In some models this local salinity in the top model layer, and in others a constant salinity. The flux  $f_s$  has units of  $\text{PSU} \text{s}^{-1}$  and the negative sign means that adding  
595 freshwater reduces the salinity. The flux  $f_s$  is then added as an additional term to the salinity budget calculation for the first ocean layer ( $k=0$ ).

$$\frac{dS}{dt}(t, k = 0, j, i) += f_s(t, j, i)$$



### A3 Applying compensation

In experiment C, a volume compensation is applied to conserve salt and prevent the global salinity from drifting. To do this we first calculate the total salinity flux added

$$F_{tot}(t) = \int h(j,i)S_0(t,j,i)dx dy$$

where  $h$  and  $S_0$  are defined in A1 and A2. Then the hosing correction is this total flux divided by the volume of the ocean

$$V = \int dx dy dz$$

giving

Since  $S_0$  varies in time, this correction is calculated at each time step and is applied at all ocean grid points.

### A4 Experiment B

Ice sheet model name	Forcing scenario	ESM Forcing	RCM Forcing	Retreat percentile
NORCE CISM	SSP585	UKESM1-0-LL	MARv3.12	p05
NORCE CISM	SSP585	UKESM1-0-LL	MARv3.12	p50
NORCE CISM	SSP585	CESM2-Leo	MARv3.12	p50
NORCE CISM	SSP585	UKESM1-0-LL	MARv3.9	p50
NORCE CISM	SSP245	MPI-ESM1-2-HR	MARv3.12	p05
NORCE CISM	SSP245	IPSL-CM6A-LR	MARv3.12	p05
NORCE CISM	SSP245	CESM2	MARv3.12	p25
NORCE CISM	SSP245	CESM2	MARv3.12	p05



Ice sheet model name	Forcing scenario	ESM Forcing	RCM Forcing	Retreat percentile
NORCE CISM	SSP245	IPSL-CM6A-LR	MARv3.12	p25

**Table A4.1. PROTECT ice sheet models selected as forcing for experiment B. Member with different retreat of marine-terminating outlet glaciers parametrization are included.**

### Code, data, or code and data availability

610 The zenodo repository allowing for computation of the mask around Greenland used in experiment A and B is coming from NAhosMIP protocol (Jackson et al. 2023) is available here: <https://zenodo.org/records/7225014>. Masks for experiment C and D are straightforward and are left for each group to be computed using their own native grid.

The zenodo repository where mass balance time series from Experiment B (cf. Fig. 3) are available at:

<https://zenodo.org/records/18609850> (Swingedouw, 2026). The diagnostic request for the TIPMIP ESM and OCEAN phase

615 1 experiments is available at <https://doi.org/10.5281/zenodo.15189530> (Licon-Salaiz, 2025).

### Author contributions

DS, LJ, AH WW, AR and NL designed the experiments, prepared the manuscript with contributions from all co-authors.

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