https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

The Southern Ocean Freshwater release model experiments Initiative (SOFIA): Scientific objectives and experimental design

Neil C. Swart[1], Torge Martin[2], Rebecca Beadling[3], Jia-Jia Chen[4], Matthew H. England[5], Riccardo Farneti[6], Stephen M. Griffies[7,8], Tore Hattermann[9], F. Alexander Haumann[10,8], Qian Li[11], John Marshall[11,14], Morven Muilwijk[9], Andrew G. Pauling[12], Ariaan Purich[13], Inga J. Smith[12], and Max Thomas[12]

[1]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC, Canada.
[2]GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
[3]Temple University, Earth and Environmental Science Department, Philadelphia, PA, USA
[4]College of Oceanography, Hohai University, Nanjing, China
[5]Climate Change Research Centre, University of New South Wales, Australia
[6]Earth System Physics Section, International Centre for Theoretical Physics, Trieste, Italy
[7]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA
[8]Atmospheric and Oceanic Sciences Program, Princeton University, Princeton, NJ, USA
[9]Norwegian Polar Institute, Fram Centre, Tromsø, Norway
[10]Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany
[11]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA
[12]Department of Physics, University of Otago, Dunedin, New Zealand
[13]School of Earth, Atmosphere and Environment, and ARC Special Research Initiative for Securing Antarctica's Environmental Future, Monash University, Melbourne, Australia
[14]NASA Goddard Institute for Space Studies, New York, NY, USA

Correspondence: Neil Swart (neil.swart@ec.gc.ca)

Abstract. As the climate warms, the grounded ice sheet and floating ice shelves surrounding Antarctica are losing mass at an increasing rate and injecting the resulting meltwater into the Southern Ocean. This freshwater input could feed back onto climate change, particularly since the Southern Ocean is a key contributor to global heat and carbon uptake. Nonetheless, almost all existing coupled climate models have fixed ice sheets, and lack the physics required to represent the dominant sources of Antarctic melt. These missing ice dynamics represent a key uncertainty that is unaccounted for in current global climate change projections. Previous studies have inserted additional Antarctic meltwater into models, demonstrating that it can alter Southern Ocean stratification, circulation, and sea ice, as well as influence remote atmospheric circulation, tropical precipitation, and global temperature. However, these previous studies have used widely varying rates of freshwater forcing, been conducted using different climate models and configurations, and have reached differing conclusions on the magnitude of meltwater-climate feedbacks. The Southern Ocean Freshwater release model experiments InitiAtive (SOFIA) brings together a team of scientists to quantify the climate system response to Antarctic meltwater input. In this paper, we summarize the state of knowledge on meltwater discharge from the Antarctic ice sheet and ice shelves to the Southern Ocean and explain the scientific objectives of our initiative. We propose a series of coupled and ocean/sea-ice model experiments, including idealized meltwater experiments, historical experiments with observationally consistent meltwater input, and future scenarios driven by

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

meltwater inputs derived from stand-alone ice sheet models. Through coordinating a multi-model ensemble of simulations, with data housed in a common archive, SOFIA will be able to produce a consistent estimate of the climate system response to Antarctic meltwater, as well as the uncertainty of this response.

1 Introduction

The Southern Ocean significantly influences anthropogenic climate change and its global consequences. As the largest relative contributor to the oceanic sink of both anthropogenic heat and carbon, processes at work in the Southern Ocean directly modulate the rate of global change (Roemmich et al., 2015; Khatiwala et al., 2009; Frölicher et al., 2015; Gruber et al., 2019; Meredith et al., 2019). The Southern Ocean also exerts a direct influence on sea-level rise, as interactions with the warming ocean are the primary driver of the observed melting of ice shelves around West Antarctica, that in turn leads to mass loss from the grounded Antarctic Ice Sheet (AIS) (Fox-Kemper et al., 2021; DeConto and Pollard, 2016; Pritchard et al., 2012). Observations over recent decades show that mass loss from Antarctica is accelerating in the regions of rapid ice shelf melt (Shepherd et al., 2018; Rignot et al., 2019). Standalone ice sheet models project that this mass loss will continue to accelerate in the future, with the resulting freshwater input to the Southern Ocean becoming a primary contributor to global sea level rise in coming decades and centuries (Fox-Kemper et al., 2021). This input of freshwater to the Southern Ocean from melting of the grounded ice sheet and the fringing floating ice shelves is expected to have significant impacts that feed back on global climate change (Fyke et al., 2018; Bronselaer et al., 2018; Dong et al., 2022). However, interactive ice sheets and shelves have generally not been included in coupled climate model simulations, including those used in the latest generation of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016). Thus, any feedbacks between ice sheets, ice shelves, and the global climate system are unaccounted for in CMIP6. This lack of inclusion of ice-climate feedbacks in coupled climate simulations represents a major source of uncertainty in future climate projections (Fyke et al., 2018; Bronselaer et al., 2018; Sadai et al., 2020).

Previous studies have attempted to quantify the impacts of Antarctic meltwater on the global climate system through the use of idealized freshwater perturbation experiments in which additional freshwater is imposed in a coupled climate model or ocean/sea-ice simulation (Table 1). However, these previous studies have used widely varying experimental designs, including differing magnitudes and spatio-temporal distributions of freshwater forcing, and differing methods to impose freshwater and heat fluxes associated with the melting ice. These studies have also been conducted using various model configurations including intermediate complexity models, CMIP-class coupled atmosphere-ocean models with varying horizontal resolutions (typically 1°), and finer resolution ocean-sea ice simulations ($< 0.25^\circ$). The results have revealed some model responses that appear to be qualitatively robust to additional freshening in the Southern Ocean, such as cooling of Southern Hemisphere sea and air surface temperatures, expansion of Antarctic sea ice, accumulation of heat at depth, and a reduction in Antarctic Bottom Water (AABW) formation. However these studies often disagree on the magnitude of the response and in some cases have reached opposing conclusions, for example on subsurface thermal changes on the continental shelf (Beadling et al., 2022), and

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

of the magnitude of the meltwater impact on historical sea-ice trends (e.g. Bintanja et al., 2013; Swart and Fyfe, 2013; Pauling et al., 2016).

The inconsistency in experimental design across previous studies inhibits our ability to constrain the climate impacts of Antarctic mass loss and the uncertainties associated with not accounting for this forcing in climate projections. Since virtually all existing Southern Ocean hosing experiments have involved only one model, the role of model uncertainty in response to freshwater is unknown. As coupled climate models evolve to include more comprehensive representations of ice sheet-ocean interactions (e.g. Siahaan et al., 2022; Smith et al., 2021), understanding the response of the climate system to Antarctic-derived freshwater, and its uncertainties, are key to the successful development of these emerging fully coupled models (Fyke et al., 2018). Indeed, understanding the future evolution of the real climate system and its impact on society requires better quantification of the important feedback associated with meltwater-derived freshwater input to the ocean (Fyke et al., 2018). Robustly quantifying the climate response to freshwater input, and its uncertainty requires a new multi-model ensemble incorporating a coordinated experimental design.

The intention of the Southern Ocean Freshwater release model experiments InitiAtive (SOFIA) is to bring together climate modelling groups to conduct coordinated experiments to quantify the climate response to Antarctic freshwater input based on a broad ensemble of ocean and climate models running the same experiments. Here, we summarize the state of knowledge on meltwater discharge from the Antarctic ice sheet and ice shelves to the Southern Ocean; explain the key scientific objectives of our initiative; and describe the design of a coordinated set of experiments that allows the consistent quantification of the impact of Antarctic meltwater on climate simulations across multiple models, as well as its key uncertainties.

2 Mass balance of Antarctic ice sheet and ice shelves

2.1 The observed mass balance

Pauling et al. (2016) provide a detailed explanation of the Antarctic ice mass budget as it relates to freshwater forcing supplied to the ocean, which we briefly summarize here. The total budget comprises two components: the first is for the grounded ice mass (M) and the second for the floating ice shelves (m). Only the grounded ice is relevant to sea-level rise. In steady state, the total grounded ice mass budget represents a balance between surface mass transports ($\dot{M}_{\mathrm{SM}}$) and mass transports across the grounding line ($\dot{M}_{\mathrm{GL}}$) so that the general mass imbalance ($\dot{M}_{\mathrm{imb}}$ would equal zero; see Fig. 1a):

$$\dot{M}_{\mathrm{SM}} + \dot{M}_{\mathrm{GL}} = \dot{M}_{\mathrm{imb}} \tag{1}$$

where positive tendencies lead to mass gain for the ice sheet. Runoff is considered a result of the local surface mass balance and thus already lost to the ice sheet mass. In a changing climate, the grounded mass can be altered via changes in the surface mass balance, or via changes in transport across the grounding line. Observations suggest that the grounded ice sheet has lost a total of 2720 ± 1390 Gt between 1992 and 2017 (Shepherd et al., 2018). This mass loss from the grounded ice sheet is rapidly accelerating, increasing from 49 ± 67 Gt yr^{-1} over 1992 to 1997, to 219 ± 43 Gt yr^{-1} over 2012 to 2017 (Shepherd et al., 2018).

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Study	Model	Function	Depth	Max input	Max input
			m	$\times 10^3$ Gt yr^{-1}	Sv
Hansen et al. (2016)	C	E	S	9.46 to 255.47	0.30 to 8.10*
Sadai et al. (2020)	C	V	S	25.23, 78.85	0.80, 2.50*
Ma et al. (2013)	C	C	S	31.54	1.00*
Stouffer et al. (2007)	C	C	S	31.54	1.00*
Bronselaer et al. (2018)	C	V	S	18.92	0.60*
Mackie et al. (2020)	C	E	R	17.71*	0.56
Purich and England (2023)	C	L	S	4.81 to 16.65	0.15 to 0.53
Golledge et al. (2019)	C	V	S	5.05*	0.16
van den Berk and Drijfhout (2014)	C	E	S	5.05*	0.16
Li et al. (2023b)	C	C	U	0.50, 2.0, 5.0*	0.02, 0.06, 0.16
Fogwill et al. (2015)	C	C	S	2.18 to 6.59	0.07 to 0.21*
Pauling et al. (2017)	C	L	R	4.10*	0.13
Beadling et al. (2022)	C	C	S	3.15	0.10*
Bronselaer et al. (2020)	C	C	S	3.15	0.10*
Park and Latif (2019)	C	C	S	1.58, 3.15	0.05, 0.10*
Rye et al. (2020)	C	V	U	0.74*	0.02
Bintanja et al. (2013)	C	C	S	0.25*	0.01
Pauling et al. (2016)	C	C	R	0.17 to 3.00*	0.01 to 0.10
Bintanja et al. (2015)	C	C	S	0.01 to 0.12*	<0.01
Swingedouw et al. (2009)	I	C	S	3.15 to 63.08	0.1 to 2.00*
Weaver et al. (2003)	I	L	S	6.31	0.20*
Aiken and England (2008)	I	C	S	0.13, 12.62	<0.01, 0.40*
Menviel et al. (2010)	I	C, L	S	5.68, 11.04	0.18, 0.35*
Swart and Fyfe (2013)	I	L	S	0.09 to 0.95	<0.01 to 0.03*
Lago and England (2019)	O	E	S	3.15	1.00
Moorman et al. (2020)	O	C	S	1.32, 5.05	0.04, 0.16*
Li et al. (2023a)	O	L	S	2.52	0.08*
Merino et al. (2018)	O	C	R	0.28*	<0.01
Seidov et al. (2001)	O	C	S	0.38 to 1.89	0.01 to 0.06*
Haumann et al. (2020)	O	C	U	0.84	0.03*

Table 1. Survey of recent studies inserting freshwater forcing into coupled or ocean only models. Model refers to fully coupled (C), intermediate complexity (I), or ocean-only (O); Function is the freshwater forcing function with time, one of constant (C), linear (L), exponential (E), or variable (V); Depth is the depth of freshwater input being at the surface (S; <50 m), with a uniform distribution (U) or a realistic distribution (R), and the maximum freshwater input applied in the study is given in both Gt yr^{-1} and Sv. Where values were not clear, they were left blank. The list of studies in this table is not exhaustive but covers the range of forcing used in previous work. The value marked with an asterisk (*) was derived from the literature, and the other value was computed using 1 Sv=3.154×10^4 Gt yr^{-1}, and all are reported to two places to facilitate comparison.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

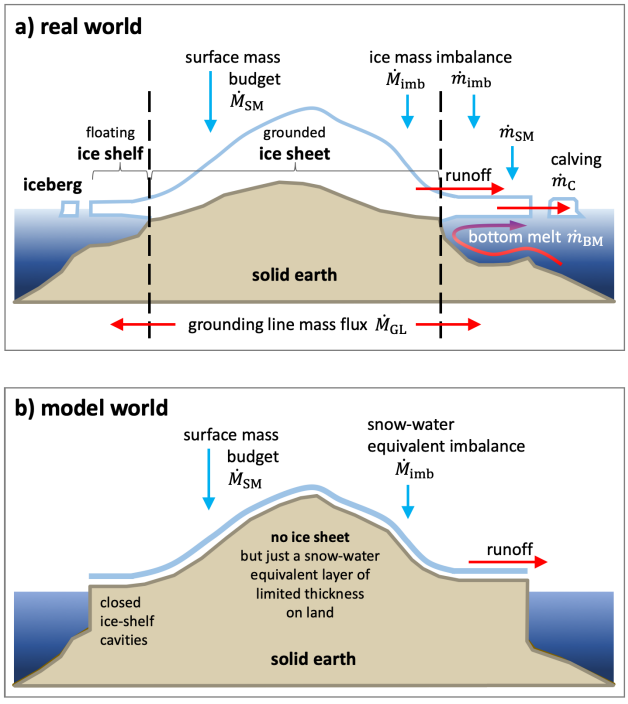

Figure 1. A schematic showing the key components of the Antarctic ice mass budget in (a) the real world and (b) the representation of the budget in typical CMIP6-class coupled climate models. In reality, the total ice mass consists of grounded ice (M) and floating ice shelves (m). Mass change over time is noted as $\dot{M}$ or $\dot{m}$ and considered positive for mass gain. Red arrows indicate transport directions associated with a negative sign in the respective mass budget. In contrast, most models only consider a snow-water equivalent layer of limited mass M_{swe} for surface mass balance and runoff calculations. Some models distinguish between liquid and solid runoff (snow) though with the latter often denoted as discharge. After Pauling et al. (2016), their Fig. 1.

The second component of the mass budget is associated with floating ice shelves (see Fig. 1a). The ice shelves receive mass from the grounded ice via transport across the grounding line ($\dot{M}_{\mathrm{GL}}$), exchange mass with the atmosphere via their surface ($\dot{m}_{\mathrm{SM}}$), and lose mass via basal melt ($\dot{m}_{\mathrm{BM}}$) and calving of icebergs ($\dot{m}_{\mathrm{C}}$).

$$\dot{m}_{\mathrm{SM}} + \dot{m}_{\mathrm{BM}} + \dot{m}_{\mathrm{C}} - \dot{M}_{\mathrm{GL}} = \dot{m}_{\mathrm{imb}} \tag{2}$$

Here, the grounding line transport is consider negative in the predominant case of ice sheet mass loss and ice shelf mass gain. Climatologically, calving and basal melt are roughly equivalent in magnitude (Rignot et al., 2013; Depoorter et al., 2013; Greene et al., 2022). It is important to note that while changes in the mass balance of floating ice shelves do not affect sea-level rise directly, they do affect the liquid freshwater input to the Southern Ocean, and thus ocean circulation and climate. Furthermore, through their mechanical coupling to the grounded ice (buttressing), ice shelf thinning is believed to accelerate the mass transport across the grounding line (Reese et al., 2018). Observational studies show that overall, the Antarctic ice shelves have been losing mass since the early 1990's when suitable satellite observations began (Adusumilli et al., 2020; Paolo

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

et al., 2015; Rignot et al., 2013; Shepherd et al., 2010). Paolo et al. (2015) found mass loss due to ice shelf thinning by basal melt was small between 1994 and 2003, but increased to 288 ± 69 Gt yr^{-1} (~ 0.009 Sv) between 2003 and 2012. More recent satellite data revealed that mass loss from the ice shelves due to basal melt slowed down in the 2010s relative to the previous decade, and that the excess meltwater transport over the longer period 1994 to 2018 was about 161 ± 147 Gt yr^{-1} (~ 0.005 Sv) (Adusumilli et al., 2020; Slater et al., 2021). Net mass loss due to calving has increased in recent decades, reaching 250 ± 68 Gt yr^{-1} in the 2010s (Slater et al., 2021).

To estimate the total freshwater input to the Southern Ocean, the net mass loss from grounded ice and floating ice shelves has to be added. For the decade of the 2010's, Slater et al. (2021) give a total mass loss rate of 509 ± 186 Gt yr^{-1} (0.017 ± 0.006 Sv; see Fig. A1b). Summing the grounded and floating ice shelf numbers of Shepherd et al. (2018) and Greene et al. (2022) provides a comparable estimate. This additional freshwater transport entering the Southern Ocean over recent decades can be regarded as the transport that is unaccounted for by CMIP6 models, assuming approximate mass balance before this time (Pauling et al., 2016, see below). We use these numbers to inform the freshwater input in our historical experiments described in Section A4.3. Note that the time at which the net ice mass balance left its presumable pre-industrial steady state and mass loss began is not precisely known. In addition, the influence of long-term natural variability in the observed estimates is also not known, but likely contributes to, for example, differences in reported ice shelf thinning (Adusumilli et al., 2020; Paolo et al., 2015). From trends in available observations, and the rate of known anthropogenic warming in the climate system, we infer that forced net mass loss around Antarctica before 1970 was likely negligible.

2.2 Antarctic meltwater discharge in coupled climate models

Coupled climate models represent many significant sources of freshwater forcing to the Southern Ocean, including that from net precipitation (Precipitation-Evaporation; P-E), surface runoff (R), and in some configurations iceberg calving (typically with a fixed, prescribed calving flux). Some models distinguish between liquid and solid (snow) runoff where the latter could serve as input mass transport to an interactive iceberg module (Martin and Adcroft, 2010). There is also freshwater redistribution via sea ice formation, transport and melt, with dynamic-thermodynamic interactive sea-ice components being state-of-the-art in such models. However, due to their large computational expense, long timescales, and sensitivity to background climate, fully interactive ice sheet and ice shelf components, or even ice shelf cavities for the ocean, have generally not been included in coupled climate models, including those participating in CMIP6 (Fox-Kemper et al., 2021; Siahaan et al., 2022).

In these models, ice-sheet coverage is typically prescribed as fixed, with any imbalances in surface mass balance carried to the ocean via runoff, although the exact details vary (see Fig. 1b; e.g. Pauling et al., 2016; Swart et al., 2019). This runoff implicitly represents the calving and basal melt transport which balances the accumulation of ice mass over land resulting from positive net precipitation (some models have explicit calving instead of pure runoff). The instantaneous runoff may respond to future changes in surface mass balance on time scales very different from those of the real ice sheet. In fact, liquid runoff from the Antarctic ice sheet is insignificant (due to low atmospheric temperatures year-round), while most of the snow that is deposited will remain on the continent for centuries or even millennia and become part of the glaciological cycle, before being discharged at the coast. Interactions between the Antarctic ice sheet and the ocean and dynamical ice sheet changes remain

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

unaccounted for, despite these processes being the primary drivers of Antarctic mass loss in the real world (Fox-Kemper et al., 2021; Shepherd et al., 2018). For example, increasing basal melt, and acceleration of mass transport across the grounding line are not represented in CMIP6 models. Owing to their highly simplified ice sheet physics, CMIP6 class climate models are thus missing an important feedback associated with the growing source of meltwater input into the Southern Ocean. The SOFIA project aims to systematically test the climate effect of including this missing freshwater forcing using the coordinated experiments described in Section A below.

2.3 Projected changes in future ice sheet mass

Process based numerical ice sheet models are the recommended tools for producing long term projections of Antarctic ice mass (Fyke et al., 2018). As described above, integrating ice sheet models directly into coupled climate simulations is challenging, and hence the primary approach to date has been to take ocean and atmospheric climate fields from climate models and using these to force stand-alone ice sheet models to produce future projections of ice mass (Edwards et al., 2021; Seroussi et al., 2020; DeConto and Pollard, 2016; Golledge et al., 2019).

The magnitude of future mass loss projected by these ice-sheet models is highly uncertain, due both to uncertainties in the input climate scenarios and potential dynamic instabilities in the ice sheet response to this forcing (Fox-Kemper et al., 2021; Edwards et al., 2021; Seroussi et al., 2020; Edwards et al., 2019; DeConto and Pollard, 2016). The latter notably arises from major uncertainties relating to marine ice sheet and ice cliff instability (Fox-Kemper et al., 2021; Edwards et al., 2019). As a result, a large range of excess freshwater input rates have been used in previous coupled modelling studies (Table 1). As increasing Antarctic meltwater enters the Southern Ocean, its potential to feedback onto the global climate system is a compounding uncertainty (Fyke et al., 2018). There are some emerging coupled modelling systems that include key ice sheet processes (e.g. Siahaan et al., 2022), but these are not yet widely employed. The approach we take in Appendix A is to obtain future freshwater forcing from an ensemble of ice sheet models run under two different scenarios, spanning the broad uncertainty range in future climate forcing, and applying this forcing to coupled climate or ocean/sea-ice models.

3 Scientific objectives

3.1 The climate response to freshwater forcing

A major objective of SOFIA is to quantify the pattern and magnitude of the climate system response to freshwater input associated with melt of the Antarctic ice sheet (see Fig. 2). Previous studies have shown that freshwater input affects ocean stratification and the thermohaline structure, large scale ocean circulation including the Antarctic Circumpolar Current, the Meridional Overturning Circulation, and circulation regimes along the Antarctic continental shelves (Beadling et al., 2022; Mackie et al., 2020; Sadai et al., 2020; Aiken and England, 2008). A key area of scientific interest is the impact of meltwater on sea-ice extent and trends, which is an area of particular disagreement in previous literature (Bintanja et al., 2013; Swart and Fyfe, 2013; Pauling et al., 2016, 2017). Furthermore, feedbacks have been hypothesized, where increased meltwater input fur-

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

ther enhances on-shore ocean heat transport through different processes in different regions (Hellmer et al., 2017; Hattermann, 2018; Bronselaer et al., 2018).

Responses to meltwater input are not confined to the Southern Ocean, but are also known to impact, for example, global surface air temperature (Sadai et al., 2020; Mackie et al., 2020; Park and Latif, 2019; Bronselaer et al., 2018; Hansen et al., 2016). Indeed, meltwater addition can reduce the climate sensitivity, making it a key process to include in future climate projections (Dong et al., 2022). Beyond temperatures, meltwater addition can influence precipitation, both regionally, and remotely through shifts in the Intertropical Convergence Zone (ITCZ) (Bronselaer et al., 2018; Park and Latif, 2019; Mackie et al., 2020; Sadai et al., 2020). Teleconnections between freshwater-induced Southern Ocean change, and remote parts of the climate system are of key interest, and can be formed through both oceanic and atmospheric pathways (Dong et al., 2022; Cabré et al., 2017; Ma and Wu, 2011). Southern Ocean freshwater input will also likely have an influence on biological production, ocean carbon uptake, and ocean acidification in this key region which connects the atmosphere to the deep ocean (Frölicher et al., 2015; Marshall and Speer, 2012; Hattermann and Levermann, 2010; Russell et al., 2006; Sarmiento et al., 2004; Toggweiler and Samuels, 1995).

The model experiments described here are intended to enable quantification of these key impacts of Antarctic meltwater on the climate system. The SOFIA multi-model ensemble will provide an estimate of the response to idealized freshwater input under pre-industrial climate conditions, under observationally plausible historical rates of freshwater input (and climate forcing), and under a range of future freshwater scenarios. Central to the SOFIA effort is improved quantification of key uncertainties in the climate response to Antarctic meltwater forcing, which we expand on below following the uncertainty breakdown of Hawkins and Sutton (2009).

3.2 Quantifying uncertainty

3.2.1 Model uncertainty

Since virtually all existing Southern Ocean hosing experiments have involved only one model, the role of model uncertainty in response to freshwater is unknown. Running the coordinated suite of simulations proposed by SOFIA across a diversity of models will allow us to address how the response to Southern Ocean freshwater release depends on differing model physics and numerics. At the time of writing, nine models have indicated an interest in participating in the project (Table 2). We invite additional models to participate, and indeed the intention of this paper is to formalize the experiments to encourage broad and diverse participation.

The nine models participating so far have differing horizontal and vertical resolutions, ocean vertical coordinates, parameterization schemes to represent sub-gridscale processes, numerics, and underlying mean-state model biases. Of particular relevance is whether models exhibit deep open-ocean convection or not (de Lavergne et al., 2014; Reintges et al., 2017). Other relevant processes that may impact a model's response to Antarctic meltwater include the underlying thermal state and stratification of the Southern Ocean, and the mechanisms of dense water formation, such as whether Antarctic Bottom Water (AABW) is formed realistically as dense shelf waters (DSW) or though open-ocean convection (Dufour et al., 2017; Lockwood et al.,

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

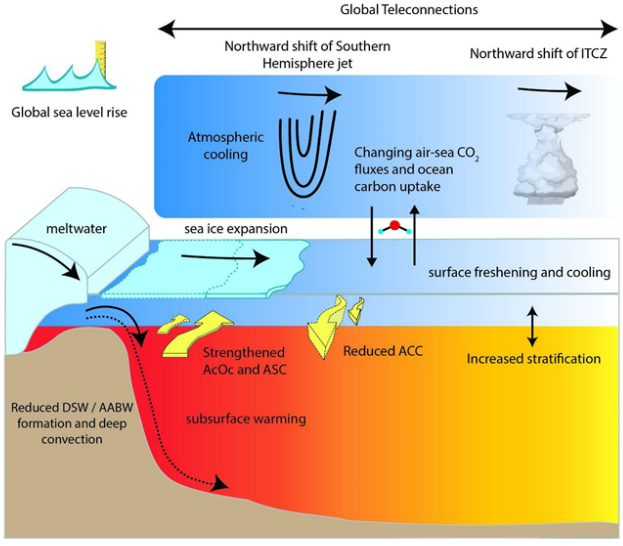

Figure 2. A schematic showing the key impacts of Antarctic ice sheet meltwater forcing on the climate system. Relevant changes in ocean circulation are highlighted including changes in the Antarctic Slope Current (ASC), Antarctic Coastal Current (AcOc), Antarctic Circumpolar Current (ACC), Dense Shelf Water (DSW) and Antarctic Bottom Water (AABW) formation.

2021; Mohrmann et al., 2021; Heuzé, 2021). Sampling across a range of models that have different representations of such processes will enable quantification of differing responses to Antarctic meltwater due to model uncertainty.

3.2.2 Internal variability

Internal climate variability is significant in the Southern Ocean, and has the potential to influence the climate system response to Antarctic melt (Beadling et al., 2022; Swart and Fyfe, 2013). To quantify the impact of internal variability on the forced response, the experimental design proposed by SOFIA encourages the production of multiple ensemble members. Of particular note are the large, multi-decadal to centennial scale oscillations in Southern Ocean properties known to exist in many CMIP-class climate models due to open-ocean deep convective events (Martin et al., 2013; Zanowski and Hallberg, 2017; Zhang et al.,

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Type	Model	Resolution (ocn/atm, lat×lon, °)	Contact	Reference
Coupled	ACCESS-ESM1-5	1/1.875×1.25	Ariaan Purich	Ziehn et al. (2020)
	CanESM5	1/3	Neil Swart	Swart et al. (2019)
	FOCI	0.5/1.9	Torge Martin	Matthes et al. (2020)
	GFDL-CM4	0.25/1	Stephen Griffies	Held et al. (2019)
	GFDL-ESM4	0.50/1	Stephen Griffies	Dunne et al. (2020)
	GISS-E2-1-G	1×1.25/2×2.5	Qian Li	Kelley et al. (2020)
	HadGEM3-GC3.1-LL	1/1	Max Thomas	Kuhlbrodt et al. (2018)
	NorESM2-MM	1/1	Tore Hattermann	Seland et al. (2020)
Ocean	MOM5	1	Riccardo Farneti	Griffies (2012)

Table 2. Models that have submitted data for the SOFIA *antwater* experiment at the time of writing. Resolution refers to the nominal horizontal resolution of the model component. A contact person for the simulations and model reference paper are also provided.

2019; Purich and England, 2021). We aim to enable an understanding of how the magnitude and patterns of the forced response depend on the phase of these internal oscillations, with more detailed description for generating the ensemble members given in Appendix A3.

3.2.3 Forcing uncertainty

Section 2 described the uncertainties in both historical and future rates of Antarctic meltwater forcing. In the experimental design described below (Appendix A), we include multiple experiments over the historical and future periods designed to test the sensitivity to the rate of freshwater forcing. There are also uncertainties in both the horizontal and vertical distribution of freshwater input to the ocean, as discussed for example in Pauling et al. (2016). In SOFIA, we focus on assessing the sensitivity to horizontal distribution, as changes in horizontal distribution of freshwater are relatively easy to implement in the participating models. On the other hand, while applying freshening at depth is possible in some modelling systems, it would be a difficult adjustment in many of the participating models. Hence to maximize participation, we have not included any explicit experiments testing the sensitivity to the depth distribution of freshwater input, although this could be tested in the future with capable models. Whether the latent heat required to melt the ice resulting in freshwater input is extracted from the ocean or not is a further uncertainty (Pauling et al., 2017), and we include an experiment to test this sensitivity. Finally, because there might be interactions between freshwater forcing and other climate forcings such as greenhouse gases, we aim to test the impact of freshwater forcing both alone (e.g. under piControl conditions), and in combination with other forcings (e.g. under historical and SSP conditions).

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

4 Future work and activities

The immediate goal of SOFIA is to encourage the participation of a wide and diverse group of models in the experiments described here. The larger and more diverse the participating ensemble, the more robust our quantification of the climate response to freshwater forcing and its uncertainty will be. The initial group of participating models is starting to archive data for the *antwater* experiment. A series of analysis papers are being prepared, one on the general climate response to freshwater forcing, and several papers focused on particularly noteworthy aspects of the response, including the effect on deep convection and bottom water formation, and Southern Ocean circulation. We anticipate that results from the historical experiments will allow us to study important questions surrounding detection and attribution of climate changes to freshwater forcing, such as for Antarctic sea ice. Through analysis of the SOFIA future scenario runs with freshwater forcing, we aim to quantify the impact of this missing climate feedback in the CMIP6 model projections. Moreover, we aim to provide information for modelling centers trying to determine the relative importance of including ice-ocean interactions in future generations of coupled climate models, such as those being prepared for CMIP7. We invite the broader community to propose additional studies, and to make use of the SOFIA data archive (Appendix A6.2) to advance our collective understanding of the role of Antarctic meltwater on the climate system.

Data availability. SOFIA data will be provided at ftp://ftp.cccma.ec.gc.ca/pub/CCCMA/SOFIA/ - see Section A6

Appendix A: Experimental design

A1 Overall philosophy

The experimental suite designed by SOFIA builds off the CMIP6 framework for organizing our experiments and data request (Eyring et al., 2016). A tiered hierarchy of experiments is proposed to allow basic quantification of meltwater impacts in idealized and more realistic settings (Table A1). The idealized experiments provide a low barrier to entry for participants, whereas higher tier experiments explore more realistic scenarios and sensitivities. In the following sections we provide details on the model setup and realizations, the details of each experiment, as well as the data request.

A2 Model configurations and forcings

SOFIA welcomes contributions from fully coupled and ocean/sea-ice models. Many of our objectives (Section 3) relate to the broader climate system, and require coupled atmosphere-ocean models to fully address. However, additional information relating to the ocean response may also be gained by examining the response of forced ocean/sea-ice models, as done in the CMIP6 OMIP exercise (Griffies et al., 2016).

In all cases, we encourage groups to use well known and documented versions of their models. In particular, for models that participated in CMIP6, we suggest using the same configuration as used in CMIP6 for SOFIA. The same model configuration

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Name	FW perturbation (Sv)	Branch year	Time span (year)	Other forcing
Tier-1				
piControl	None	N/A	≥100	Fixed preindustrial
antwater	Fixed 0.1	Model year	≥100	Fixed preindustrial
Tier-2				
hist-antwater-70-01	Increasing by 0.1 ($\times 10^{-3}$ Sv·yr^{-1})	1970	1970-2020	historical
hist-antwater-70-03	Increasing by 0.3 ($\times 10^{-3}$ Sv·yr^{-1})	1970	1970-2020	historical
hist-antwater-70-05	Increasing by 0.5 ($\times 10^{-3}$ Sv·yr^{-1})	1970	1970-2020	historical
hist-antwater-92-11	Increasing by 1.1 ($\times 10^{-3}$ Sv·yr^{-1})	1992	1992-2020	historical
ssp126-ismip6-water	Fixed 0.015	2015	2015-2100	SSP126 scenario
ssp585-ismip6-water	Increasing nonlinearly; Maximum 0.196	2015	2015-2100	SSP585 scenario
Tier-3				
60Swater	Fixed 0.1;Imposing south 60°S	Model year	≥100	Fixed preindustrial
antwater-lh	Fixed 0.1;Extracting latent heat	Model year	≥100	Fixed preindustrial

Table A1. SOFIA experiment name, branch year from the standard CMIP6 run, the amount or increasing rate of freshwater forcing starting from the branch year, simulation year, and other external forcing.

should be used for all SOFIA experiments labelled with the same name, with only the forcing changing between experiments (if multiple physical variants are submitted, they should be clearly labelled). The SOFIA experiments build on the protocols for the CMIP6 DECK and ScenarioMIP experiments (Eyring et al., 2016; O'Neill et al., 2016). Besides the specified freshwater flux anomalies, all forcing prescriptions follow the relevant CMIP6 design.

A2.1 Distribution of freshwater anomalies

In the experiments below, two spatial distributions are defined for the implementation of freshwater anomalies. By default in all cases, the freshwater anomaly is applied at the ocean surface, which is equivalent to an adjustment in E-P-R. The *Antarctic adjacent* distribution applies the freshwater anomaly directly around the Antarctic coastline (Fig. A1a). For simplicity, the anomalies are by default applied uniformly in the model grid-cell immediately adjacent to the Antarctic coast. This means that models with different horizontal resolutions will spread the anomalies over different areas, but the area-integrated anomalies will be the same across models. Models may choose, at their discretion, to distribute the anomalies over a slightly broader

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

area immediately adjacent to the Antarctic coast. However, we recommend all anomalies are constrained within 100 km of the coastline as far as practically possible.

The *60Swater* distribution applies the freshwater anomalies uniformly over all ocean grid points south of 60°S (Fig. A1a). The intention of the *60Swater* distribution is to provide a crude approximation to the northward distribution of freshwater by icebergs. It will also facilitate comparison with previous studies using a broader distribution of freshwater (Ma and Wu, 2011; Stouffer et al., 2007; Seidov et al., 2001; Purich et al., 2018, e.g.).

A3 Initial conditions and ensemble members

For all experiments, participants are encouraged to run as many ensemble members as they can afford, to help quantify internal variability. We identify between three and ten members per model and experiment as likely optimal. For SOFIA experiments that start from the piControl (Table A1), the recommended method for spawning ensemble members is to launch the SOFIA experiments from restarts of substantially different years in the control simulation. Using this macro-initialization approach allows for sampling over decadal or longer timescale ocean variability. Micro-initialization approaches, which typically add round off level perturbations to model fields, cannot properly sample over such ocean variability, and thus are discouraged. We leave it to each participating model to decide the strategy and restart time spacing to optimally sample variability in their model, factoring in the time-scales of the dominant modes of decadal climate variability.

We also invite participating models to submit variants with alternative process representation of their models, using different parameters or parameter tunings, which might reveal different but plausible responses to freshwater input. When using different variants with different model physics, participants need to clearly identify this as a different model configuration in their output. In the CMIP6 naming convention, this is typically done using either a different 'source_id' or a different 'p' number in the model variant label.

A4 Experiments

Beyond the freshwater forcing, the experimental design below provides details of the forcing to be used in coupled models. Ocean/sea-ice modellers may apply the SOFIA freshwater perturbations in their own forcing frameworks, however, we recommend the CMIP6 OMIP-1 (Griffies et al., 2016) or OMIP-2 (Tsujino et al., 2020) experiment and protocol as a logical common choice for other forcing fields (see Appendix A5).

A4.1 piControl

The *piControl* simulation provides the model baseline state against which the Antarctic freshwater forcing simulations will be compared. For coupled models, the SOFIA *piControl* experiment is equivalent to the CMIP6 *piControl* experiment. For models that participated in CMIP6, the published *piControl* may be used. If a model has changed its configuration since CMIP6, or did not participate in CMIP6, then it should run a simulation conforming to the CMIP6 *piControl* experimental design, for at least 100 years, and preferably 500 or more years.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

A4.2 antwater

The aim of the idealized *antwater* experiment is to assess the climate response to an applied Antarctic freshwater forcing anomaly in the participating models. The *antwater* experiment is branched off the *piControl* simulation, with all other forcings the same as in *piControl*. On top of this, a freshwater flux anomaly is applied at the ocean surface in the Antarctic adjacent distribution, which when area integrated represents a constant freshwater transport of 0.1 Sv (1 Sv=3.15×10^4 Gt yr^{-1}). The simulation is run for a minimum of 100 years. The SOFIA *antwater* experiment is closely related to the CMIP6 FAFMIP experiment *faf-antwater-stress* (Gregory et al., 2016). The only difference in SOFIA *antwater* relative to *faf-antwater-stress* is that no wind-stress anomaly is applied. We note that the perturbation applied in *antwater* is substantially larger then current observational estimates and the SOFIA historical experiments (Section A4.3). However, the magnitude of freshwater forcing in *antwater* is used to produce a clear signal for the purposes of comparing model responses, is well within the range of previous studies (Table 1), is comparable to forcing magnitudes expected in the 21st century, and is used in the SOFIA future scenario experiments (Section A4.4; Fig. A1c).

A4.3 Historical experiments

The aim of the SOFIA *hist-antwater* simulations is to assess the impact of plausible rates of historical Antarctic freshwater input, in conjunction with and relative to other realistically evolving climate forcings. The *hist-antwater* experiments are branched off an existing CMIP6 or CMIP6-like *historical* experiment in the year 1970 or 1992, and run to 2020. We intentionally keep the simulations short to make the experiment more computationally affordable. Two different start dates are used because the exact point at which Antarctic mass loss began is not precisely known, although it was likely weak prior to 1970, and is only observationally contrained since the early 1990's (Section 2). All forcings and protocols from the CMIP6 *historical* experiment apply from 1970-01 to 2014-12, and from 2015-01 to 2020-12, the *ssp585* forcings are used. Since all forcing scenarios are very similar over 2015 to 2020, which scenario is used is arbitrary, and such extensions are commonly used (e.g. Gillett et al., 2016). Extending the historical experiments to 2020 will allow for a more comprehensive comparison with observations, and will provide overlap with the future scenario runs. Models without existing historical simulations can branch off the control experiment in 1850 and run under CMIP6 *historical* forcings. For ocean/sea-ice simulations, participating models can use the JRA55-do surface forcing dataset from 1958 to 2020 following the OMIP-2 framework (Tsujino et al., 2020).

Four separate historical experiments with additional meltwater forcing are proposed to span the uncertainty range in historical freshwater input (Fig. A1b). In each experiment, additional freshwater input before the branch date is zero. From the branch date onwards, a freshwater transport anomaly is applied over the *Antarctic adjacent* distribution, with a linearly increasing rate, according to Table A1. The linear rates of increase in Table A1 are given in Sv yr^{-1}, and the intention is that the input would increase linearly over the course of the year, starting on 1 Jan of branch year, and increasing by the annual increment by 31 December. How exactly modelling centres implement the increase (e.g. as monthly means, or at the time-step level), will slightly influence the amount of input, but this method-based variance is small compared to the annual amount of freshwater being

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

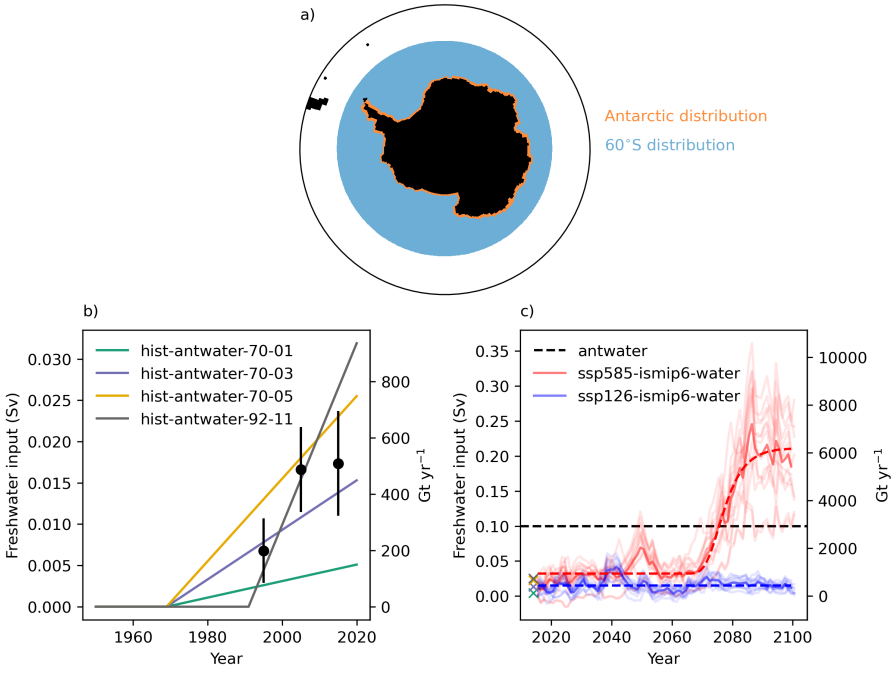

Figure A1. SOFIA forcing. a) The horizontal distribution of freshwater inputs, b) rate of freshwater input in historical experiments and c) in future scenario experiments. In c), the idealized fits to the forcing described in the text are shown in dashed lines, and the rates of input in historical experiments in 2014 are shown by x's. The lighter red lines show the the basal melt rate simulated by individual ISMIP6 models, multiplied by $1/0.55$ to account for calving. In b) the central black dots and error bars represent the summed ice shelf plus Antarctic grounded ice loss estimates from (Slater et al., 2021). In b) and c) we show both units of Gt yr^{-1} (with lines computed using the equations in the text) and Sv, using the conversion 1 Sv=3.154×10^4 Gt yr^{-1}.

added. The span of freshwater input magnitudes across the experiments will allow us to quantify how uncertainty in historical rates of ice sheet melt affect the climate response.

In these experiments, the cumulative freshwater input ranges from 4101 Gt in the *hist-antwater-70-01* experiment to 20506 Gt in the *hist-antwater-70-05* experiment. In the *hist-antwater-92-11* experiment, the cumulative input amounts to 14587 Gt and the average transport is 0.0165 Sv (521 Gt yr^{-1}). Both measures in this experiment agree closely with the current best estimate of the observed combined changes of the grounded ice sheet (Shepherd et al., 2018) and the floating ice shelves (Greene et al., 2022) (Section 2). The maximum input of about 0.03 Sv by the end of the historical experiment is at the lower end of the maximum input applied in previous modelling experiments (Table 1).

A4.4 Future scenarios

The aim of the SOFIA future scenario simulations is to assess the impact of possible rates of future Antarctic freshwater input, in conjunction with and relative to other evolving climate forcings. As climate forcings, we use one low end (SSP126) and one

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

high end (SSP585) emission scenario from CMIP6 ScenarioMIP (O'Neill et al., 2016). To these we add freshwater forcing, which is derived from the basal melt rates generated by offline ice sheet models participating in the Ice Sheet Model Intercomparison for CMIP6 (ISMIP6) under the equivalent CMIP5 climate forcings (RCP2.6 and RCP8.5, respectively; Seroussi et al., 2020). To account for additional iceberg calving, we divide the ISMIP6 basal melting rate by a factor of 0.55, following the fraction of basal melt to calving given in Rignot et al. (2013).

The SOFIA scenario experiments are branched off a regular CMIP6 or CMIP6-like *historical* experiment instead of the *hist-antwater* experiments. Branching from a standard *historical* run makes the experiments more modular - groups could run only future scenarios if they choose. Further, in the high end warming scenario (SSP585) the freshwater forcing in the future is considerably stronger than the historical freshwater forcing, implying that starting from a zero freshwater transport anomaly in 2015 is a reasonable approximation given the scale of the future freshwater increase. Figure A1c shows the SOFIA scenario freshwater input rates, along with idealized fits described below.

A4.5 ssp126-ismip6-water

The *ssp126-ismip6-water* experiment is branched off a CMIP6 or CMIP6-like *historical* experiment and runs for at least 86 years, from 2015 to at least 2100. In coupled models, all forcings and protocols from the CMIP6 *ssp126* experiment apply. In addition to this, a freshwater transport anomaly is applied over the *Antarctic adjacent* distribution at a rate which is determined from the ensemble mean basal melt rate from ISMIP6 under RCP26 forcing (Seroussi et al., 2020). This rate is then multiplied by $1/0.55$ to account for calving fluxes, following the basal melt to calving ratios in Rignot et al. (2013). For simplicity, this total forcing can be approximated by a constant input of 0.015 Sv (475 Gt yr^{-1}, Fig. A1c, blue dashed line), which approximately matches the current observed rate (Section 2) and the rate of the historical experiments (Section A4.3; crosses in Fig. A1c).

A4.6 ssp585-ismip6-water

The *ssp585-ismip6-water* experiment is branched off a CMIP6 or CMIP6-like *historical* experiment and runs for 86 years from 2015 to 2100. If possible, we encourage modellers to extend their simulations to 2300, as some impacts of the strong ramp-up in freshwater input in this scenario might have long timescale responses. If extending beyond 2100, all forcings, including freshwater, should be held constant at 2100 levels. In coupled models, all forcings and protocols from the CMIP6 *ssp585* experiment apply. In addition to this, a freshwater transport anomaly is applied over the *Antarctic adjacent* distribution at a rate which is determined from the ensemble mean basal melt rate from ismip6 under RCP85 forcing. As for *ssp126-ismip6-water*, this rate is then multiplied by $1/0.55$ to account for additional calving fluxes.

For convenience in applying the forcing in models, we have produced a generalized logistic fit for the total freshwater forcing (Fig. A1c, red dashed line). This fit is given by:

$$y(t) = \frac{1}{0.55}\left(A + \frac{K - A}{(1 + Q.e^{-Bt})^{1/v}}\right) \tag{A1}$$

where the coefficients are given in Table A2, and t is the number of years since 2015 (with t starting at 0 in 2015).

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Coefficient	Value	Units
A	5.18×10^2	Gt yr^{-1}
K	3.41×10^3	Gt yr^{-1}
B	0.21	yr^{-1}
v	3.85×10^{-5}	
Q	1.48×10^1	

Table A2. Coefficients of the generalized logistic fit from Equation A1 to the freshwater forcing to be applied in the SOFIA *ssp585-ismip6-water* experiment.

A4.7 Idealized sensitivity tests

A4.8 60Swater

The *60Swater* experiment is identical to *antwater*, except for the horizontal distribution of the freshwater anomalies. In *60Swater*, the freshwater flux anomaly is applied at the ocean surface in the 60°S distribution, with an area integrated constant rate of 0.1 Sv. The intention of this experiment is to test the sensitivity of the horizontal distribution of freshwater input, and in particular, the effect that northward distribution by icebergs might have on the climate.

A4.9 antwater-lh

The *antwater-lh* experiment is identical to *antwater*, except that in addition to the freshwater anomaly applied to the ocean surface, the latent heat of melt required to melt 0.1 Sv is also extracted from the ocean surface, uniformly with the Antarctic adjacent distribution. In reality, latent heat is extracted from the ocean to induce basal melt of ice shelves and icebergs, however, this latent heat forcing is often neglected in the literature (Pauling et al., 2016, 2017; Swart and Fyfe, 2013; Bintanja et al., 2013) and indeed, in all the experiments described above, it has been excluded for simplicity. The aim of this experiment is to quantify the additional effect of including the latent heat of melt on the climate response. We do not include the heat required to bring the ice from its ambient temperature to the freezing point, as this is generally much smaller than the latent heat of melt (Slater et al., 2021).

A5 Using ocean/sea-ice models

Performing forced global ocean/sea-ice simulations requires the use of sea surface salinity (SSS) or water restoring. Surface restoring is not physical and its required strength is sensitive to the model and configuration used. However, it is necessary in order to prevent long term salinity drifts due to uncertainties in the prescribed surface forcing (Griffies et al., 2009; Danabasoglu et al., 2014; Griffies et al., 2016). When performing surface flux perturbations, such as the idealized meltwater experiments proposed in SOFIA, surface restoring would inevitably affect the perturbation-induced response in both the surface and interior

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

of the ocean. A methodology proposed for carrying out SOFIA experiments in forced ocean/sea-ice mode is detailed next, with recommendations on how to obtain stable control solutions without applying any surface restoring.

First, and after a sufficiently long spin-up, a multicentury-long control experiment is completed using SSS restoring. The restoring time scale is subject to the model but it is recommended to be as weak as possible. Also, no SSS restoring is applied under sea-ice. Models transporting water across the ocean surface, such as MOM, add or subtract fresh water impacting the ocean volume. For this reason, a global normalisation is applied at each time step at the surface so that the net water input is set to zero. We chose to force the model with the Coordinated Ocean-Ice Reference Experiment (CORE) repeating Normal Year Forcing (NYF), see Griffies et al. (2009), where the Large and Yeager (2009) atmospheric dataset is used to compute idealized repeating annual cycles for heat, moisture and momentum. An alternative approach could use the JRA55-do (Tsujino et al., 2018) 1984-1985 Repeat Year Forcing (RYF; Stewart et al., 2020). In both cases, air-sea fluxes are diagnosed through bulk formulae.

During the last 100 years of the control simulation, SSS restoring-induced surface freshwater fluxes are saved with a recommended frequency of 6 hours, as daily fluxes have been proven to be not sufficient to reproduce a stable solution. Then, a twin control is performed, reproducing the last 100 years of the control simulation, but with SSS restoring deactivated and adding as salt correction the 6-hourly SSS fluxes from the restoring simulation. Hence, following the method described in Boeira Dias et al. (2020, 2021), in this case no SSS restoring is applied and only the restoring-induced fluxes are prescribed to the ocean/sea-ice model. Imposing 6-hourly SSS restoring-induced fluxes results in negligible changes in globally averaged SST, SSS and volume-average temperature and salinity. Standard metrics such as the ACC and AMOC strength present a stable behavior during the entire length of both controls, with no significant modifications in transports.

Now that a control simulation without SSS restoring is available, serving the same purpose as a piControl experiment for coupled models (section A4.1), the idealized antwater experiment (section A4.2) can be carried out by adding to the SSS restoring-induced fluxes the SOFIA freshwater perturbations during the entire 100 year period.

Given the deterministic behavior within a forced ocean/sea-ice simulation and the limited spread achieved by perturbing the initial conditions, instead of producing an ensemble of simulations we recommend exploring the response within the parameter space of the freshwater anomalies.

For historical experiments (section A4.3), the same protocol is followed with an ocean/sea-ice model forced by either the interannual CORE-II atmospheric state (as in OMIP-1; Griffies et al., 2012; Danabasoglu et al., 2014) or the interannually varying JRA55-do surface atmospheric dataset (as in OMIP-2; Tsujino et al., 2020).

A6 Data request

A6.1 Requested variables and format

We request a sub-set of the full CMIP6 data request (Griffies et al., 2016; Juckes et al., 2020), to enable us to address our core scientific objectives, while limiting the burden on modellers and disk archives. The list of requested variables, using CMIP6 standard nomenclature, is provided in Table A3. Output according to CMIP6 standards and conventions (i.e. Coupled Model

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Output Rewriter; CMOR) is preferred. However, in the interest of a low bar for participating in SOFIA, netCDF formatted data not conforming with CMIP6 naming and metadata requirements will be accepted. In this case, models must provide sufficient information for users to interpret their data, and specifically the mapping between CMIP6 names/units and their model names/units.

A6.2 Data sharing

A common archive of key variables is housed at ftp://ftp.cccma.ec.gc.ca/pub/CCCMA/SOFIA/. Each modelling group may provide more complete output using a service of their choice.

Author contributions. NCS coordinated authors, wrote most of the original text, and made Fig. A1. TM coordinated author meetings and produced Fig. 1 ... . All authors contributed to the discussion of the experimental design and the editing of the text.

Competing interests. The authors have the following competing interests: At least one co-author is on the editorial board of GMD.

Acknowledgements. MM and TH received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003826 via project CRiceS. MHE and AP are funded by the Australian Research Council Special Research Initiative in Antarctic Science scheme (Grant Nos. SR200100008 and SR200100005).

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

References

Adusumilli, S., Fricker, H. A., Medley, B., Padman, L., and Siegfried, M. R.: Interannual variations in meltwater input to the Southern Ocean from Antarctic ice shelves, Nature Geoscience, 13, 616–620, https://doi.org/10.1038/s41561-020-0616-z, https://www.nature.com/articles/s41561-020-0616-z, number: 9 Publisher: Nature Publishing Group, 2020.

Aiken, C. M. and England, M. H.: Sensitivity of the Present-Day Climate to Freshwater Forcing Associated with Antarctic Sea Ice Loss, Journal of Climate, 21, 3936–3946, https://doi.org/10.1175/2007JCLI1901.1, https://journals.ametsoc.org/view/journals/clim/21/15/2007jcli1901.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2008.

Beadling, R. L., Krasting, J. P., Griffies, S. M., Hurlin, W. J., Bronselaer, B., Russell, J. L., MacGilchrist, G. A., Tesdal, J.-E., and Winton, M.: Importance of the Antarctic Slope Current in the Southern Ocean Response to Ice Sheet Melt and Wind Stress Change, Journal of Geophysical Research: Oceans, 127, e2021JC017 608, https://doi.org/10.1029/2021JC017608, https://onlinelibrary.wiley.com/doi/abs/10.1029/2021JC017608, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021JC017608, 2022.

Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., and Katsman, C. A.: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion, Nature Geoscience, 6, 376–379, https://doi.org/10.1038/ngeo1767, https://www.nature.com/articles/ngeo1767, number: 5 Publisher: Nature Publishing Group, 2013.

Bintanja, R., van Oldenborgh, G., and Katsman, C.: The effect of increased fresh water from Antarctic ice shelves on future trends in Antarctic sea ice, Annals of Glaciology, 56, 120–126, https://doi.org/10.3189/2015AoG69A001, publisher: Cambridge University Press, 2015.

Boeira Dias, F., Fiedler, R., Marsland, S. J., Domingues, C. M., Clement, L., Rintoul, S. R., McDonagh, E. L., Mata, M. M., and Savita, A.: Ocean heat storage in response to changing ocean circulation processes, J. Climate, 33, 9065–9082, 2020.

Boeira Dias, F., Domingues, C. M., Marsland, S. J., Rintoul, S. R., Uotila, P., Fiedler, R., Mata, M. M., Bindoff, N. L., and Savita, A.: Subpolar Southern Ocean response to changes in the surface momentum, heat and freshwater fluxes under 2xCO2, J. Climate, 34, 8755–8775, 2021.

Bronselaer, B., Winton, M., Griffies, S. M., Hurlin, W. J., Rodgers, K. B., Sergienko, O. V., Stouffer, R. J., and Russell, J. L.: Change in future climate due to Antarctic meltwater, Nature, 564, 53–58, https://doi.org/10.1038/s41586-018-0712-z, https://doi.org/10.1038/s41586-018-0712-z, 2018.

Bronselaer, B., Russell, J. L., Winton, M., Williams, N. L., Key, R. M., Dunne, J. P., Feely, R. A., Johnson, K. S., and Sarmiento, J. L.: Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean, Nature Geoscience, 13, 35–42, https://doi.org/10.1038/s41561-019-0502-8, https://www.nature.com/articles/s41561-019-0502-8, number: 1 Publisher: Nature Publishing Group, 2020.

Cabré, A., Marinov, I., and Gnanadesikan, A.: Global Atmospheric Teleconnections and Multidecadal Climate Oscillations Driven by Southern Ocean Convection, Journal of Climate, 30, 8107–8126, https://doi.org/10.1175/JCLI-D-16-0741.1, https://journals.ametsoc.org/view/journals/clim/30/20/jcli-d-16-0741.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2017.

Danabasoglu, G., Yeager, S. G., Bailey, D., Behrens, E., Bentsen, M., Bi, D., Biastoch, A., Böning, C., Bozec, A., Canuto, V. M., Cassou, C., Chassignet, E., Coward, A. C., Danilov, S., Diansky, N., Drange, H., Farneti, R., Fernandez, E., Fogli, P. G., Forget, G., Fujii, Y., Griffies, S. M., Gusev, A., Heimbach, P., Howard, A., Jung, T., Kelley, M., Large, W. G., Leboissetier, A., Lu, J., Madec, G., Marsland, S. J., Masina, S., Navarra, A., Nurser, A. J. G., Pirani, A., Salas y Mélia, D., Samuels, B. L., Scheinert, M., Sidorenko, D., Treguier, A.-M., Tsujino, H., Uotila, P., Valcke, S., Voldoire, A., and Wang, Q.: North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part I: Mean states, Ocean Modelling, 73, 76–107, 2014.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

de Lavergne, C., Palter, J. B., Galbraith, E. D., Bernardello, R., and Marinov, I.: Cessation of deep convection in the open Southern Ocean under anthropogenic climate change, Nature Climate Change, 4, 278–282, https://doi.org/10.1038/nclimate2132, https://doi.org/10.1038/nclimate2132, 2014.

DeConto, R. M. and Pollard, D.: Contribution of Antarctica to past and future sea-level rise, Nature, 531, 591–597, https://doi.org/10.1038/nature17145, https://www.nature.com/articles/nature17145, number: 7596 Publisher: Nature Publishing Group, 2016.

Depoorter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, J. T. M., Ligtenberg, S. R. M., van den Broeke, M. R., and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves, Nature, 502, 89–92, https://doi.org/10.1038/nature12567, https://doi.org/10.1038/nature12567, 2013.

Dong, Y., Pauling, A. G., Sadai, S., and Armour, K. C.: Antarctic Ice-Sheet Meltwater Reduces Transient Warming and Climate Sensitivity Through the Sea-Surface Temperature Pattern Effect, Geophysical Research Letters, 49, e2022GL101 249, https://doi.org/10.1029/2022GL101249, https://onlinelibrary.wiley.com/doi/abs/10.1029/2022GL101249, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2022GL101249, 2022.

Dufour, C. O., Morrizon, A. K., Griffies, S. M., Frenger, I., Zanowski, H., and Winton, M.: Preconditioning of the Weddell Sea polynya by the ocean mesoscale and dense water overflows, Journal of Climate, 30, 7719–7737, https://doi.org/10.1175/JCLI-D-16-0586.1, 2017.

Dunne, J. P., Horowitz, L. W., Adcroft, A. J., Ginoux, P., Held, I. M., John, J. G., Krasting, J. P., Malyshev, S., Naik, V., Paulot, F., Shevliakova, E., Stock, C. A., Zadeh, N., Balaji, V., Blanton, C., Dunne, K. A., Dupuis, C., Durachta, J., Dussin, R., Gauthier, P. P. G., Griffies, S. M., Guo, H., Hallberg, R. W., Harrison, M., He, J., Hurlin, W., McHugh, C., Menzel, R., Milly, P. C. D., Nikonov, S., Paynter, D. J., Ploshay, J., Radhakrishnan, A., Rand, K., Reichl, B. G., Robinson, T., Schwarzkopf, D. M., Sentman, L. T., Underwood, S., Vahlenkamp, H., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, Y., and Zhao, M.: The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics, Journal of Advances in Modeling Earth Systems, 12, e2019MS002 015, https://doi.org/https://doi.org/10.1029/2019MS002015, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS002015, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS002015, 2020.

Edwards, T. L., Brandon, M. A., Durand, G., Edwards, N. R., Golledge, N. R., Holden, P. B., Nias, I. J., Payne, A. J., Ritz, C., and Wernecke, A.: Revisiting Antarctic ice loss due to marine ice-cliff instability, Nature, 566, 58–64, https://doi.org/10.1038/s41586-019-0901-4, https://doi.org/10.1038/s41586-019-0901-4, 2019.

Edwards, T. L., Nowicki, S., Marzeion, B., Hock, R., Goelzer, H., Seroussi, H., Jourdain, N. C., Slater, D. A., Turner, F. E., Smith, C. J., McKenna, C. M., Simon, E., Abe-Ouchi, A., Gregory, J. M., Larour, E., Lipscomb, W. H., Payne, A. J., Shepherd, A., Agosta, C., Alexander, P., Albrecht, T., Anderson, B., Asay-Davis, X., Aschwanden, A., Barthel, A., Bliss, A., Calov, R., Chambers, C., Champollion, N., Choi, Y., Cullather, R., Cuzzone, J., Dumas, C., Felikson, D., Fettweis, X., Fujita, K., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huss, M., Huybrechts, P., Immerzeel, W., Kleiner, T., Kraaijenbrink, P., Le clec'h, S., Lee, V., Leguy, G. R., Little, C. M., Lowry, D. P., Malles, J.-H., Martin, D. F., Maussion, F., Morlighem, M., O'Neill, J. F., Nias, I., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Radić, V., Reese, R., Rounce, D. R., Rückamp, M., Sakai, A., Shafer, C., Schlegel, N.-J., Shannon, S., Smith, R. S., Straneo, F., Sun, S., Tarasov, L., Trusel, L. D., Van Breedam, J., van de Wal, R., van den Broeke, M., Winkelmann, R., Zekollari, H., Zhao, C., Zhang, T., and Zwinger, T.: Projected land ice contributions to twenty-first-century sea level rise, Nature, 593, 74–82, https://doi.org/10.1038/s41586-021-03302-y, https://www.nature.com/articles/s41586-021-03302-y, number: 7857 Publisher: Nature Publishing Group, 2021.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geoscientific Model Development, 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, https://gmd.copernicus.org/articles/9/1937/2016/gmd-9-1937-2016.html, publisher: Copernicus GmbH, 2016.

Fogwill, C. J., Phipps, S. J., Turney, C. S. M., and Golledge, N. R.: Sensitivity of the Southern Ocean to enhanced regional Antarctic ice sheet meltwater input, Earth's Future, 3, 317–329, https://doi.org/10.1002/2015EF000306, https://onlinelibrary.wiley.com/doi/abs/10.1002/2015EF000306, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2015EF000306, 2015.

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., and Yu, Y.: Ocean, cryosphere, and sea level change, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, \., Yu, R., and Zhou, B., pp. 1211–1362, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.001, 2021.

Frölicher, T. L., Sarmiento, J. L., Paynter, D. J., Dunne, J. P., Krasting, J. P., and Winton, M.: Dominance of the Southern Ocean in Anthropogenic Carbon and Heat Uptake in CMIP5 Models, Journal of Climate, 28, 862–886, https://doi.org/10.1175/JCLI-D-14-00117.1, https://journals.ametsoc.org/view/journals/clim/28/2/jcli-d-14-00117.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2015.

Fyke, J., Sergienko, O., Löfverström, M., Price, S., and Lenaerts, J. T. M.: An Overview of Interactions and Feedbacks Between Ice Sheets and the Earth System, Reviews of Geophysics, 56, 361–408, https://doi.org/10.1029/2018RG000600, https://onlinelibrary.wiley.com/doi/abs/10.1029/2018RG000600, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2018RG000600, 2018.

Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., and Tebaldi, C.: The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6, Geoscientific Model Development, 9, 3685–3697, https://doi.org/10.5194/gmd-9-3685-2016, https://gmd.copernicus.org/articles/9/3685/2016/, publisher: Copernicus GmbH, 2016.

Golledge, N. R., Keller, E. D., Gomez, N., Naughten, K. A., Bernales, J., Trusel, L. D., and Edwards, T. L.: Global environmental consequences of twenty-first-century ice-sheet melt, Nature, 566, 65–72, https://doi.org/10.1038/s41586-019-0889-9, https://doi.org/10.1038/s41586-019-0889-9, 2019.

Greene, C. A., Gardner, A. S., Schlegel, N.-J., and Fraser, A. D.: Antarctic calving loss rivals ice-shelf thinning, Nature, 609, 948–953, https://doi.org/10.1038/s41586-022-05037-w, https://doi.org/10.1038/s41586-022-05037-w, 2022.

Gregory, J. M., Bouttes, N., Griffies, S. M., Haak, H., Hurlin, W. J., Jungclaus, J., Kelley, M., Lee, W. G., Marshall, J., Romanou, A., Saenko, O. A., Stammer, D., and Winton, M.: The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: investigation of sea-level and ocean climate change in response to CO_2 forcing, Geoscientific Model Development, 9, 3993–4017, https://doi.org/10.5194/gmd-9-3993-2016, https://gmd.copernicus.org/articles/9/3993/2016/, publisher: Copernicus GmbH, 2016.

Griffies, S., Biastoch, A., Boning, C., Bryan, F., Danabasoglu, G., Chassignet, E., England, M., Gerdes, R., Haak, H., and Hallberg, R.: Coordinated Ocean-ice Reference Experiments (COREs), Ocean Modelling, 26, 1–46, 2009.

Griffies, S. M.: Elements of the Modular Ocean Model (MOM) (2012 release), GFDL Ocean Group Technical Report 7, NOAA/Geophysical Fluid Dynamics Laboratory, https://mom-ocean.github.io/assets/pdfs/MOM5_manual.pdf, 2012.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Griffies, S. M., Winton, M., Samuels, B. L., Danabasoglu, G., Yeager, S. G., Marsland, S. J., Drange, H., and Bentsen, M.: Datasets and protocol for the CLIVAR WGOMD Coordinated Ocean-sea ice Reference Experiments (COREs), WCRP Report, No. 21, pp. 1–21, 2012.

Griffies, S. M., Danabasoglu, G., Durack, P. J., Adcroft, A. J., Balaji, V., Böning, C. W., Chassignet, E. P., Curchitser, E., Deshayes, J., Drange, H., Fox-Kemper, B., Gleckler, P. J., Gregory, J. M., Haak, H., Hallberg, R. W., Heimbach, P., Hewitt, H. T., Holland, D. M., Ilyina, T., Jungclaus, J. H., Komuro, Y., Krasting, J. P., Large, W. G., Marsland, S. J., Masina, S., McDougall, T. J., Nurser, A. J. G., Orr, J. C., Pirani, A., Qiao, F., Stouffer, R. J., Taylor, K. E., Treguier, A. M., Tsujino, H., Uotila, P., Valdivieso, M., Wang, Q., Winton, M., and Yeager, S. G.: OMIP contribution to CMIP6: experimental and diagnostic protocol for the physical component of the Ocean Model Intercomparison Project, Geoscientific Model Development, 9, 3231–3296, https://doi.org/10.5194/gmd-9-3231-2016, https://gmd.copernicus.org/articles/9/3231/2016/, publisher: Copernicus GmbH, 2016.

Gruber, N., Clement, D., Carter, B. R., Feely, R. A., Heuven, S. v., Hoppema, M., Ishii, M., Key, R. M., Kozyr, A., Lauvset, S. K., Monaco, C. L., Mathis, J. T., Murata, A., Olsen, A., Perez, F. F., Sabine, C. L., Tanhua, T., and Wanninkhof, R.: The oceanic sink for anthropogenic CO_2 from 1994 to 2007, Science, 363, 1193–1199, https://doi.org/10.1126/science.aau5153, https://www.science.org/doi/abs/10.1126/science.aau5153, _eprint: https://www.science.org/doi/pdf/10.1126/science.aau5153, 2019.

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M., and Lo, K.-W.: Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous, Atmospheric Chemistry and Physics, 16, 3761–3812, https://doi.org/10.5194/acp-16-3761-2016, https://acp.copernicus.org/articles/16/3761/2016/, publisher: Copernicus GmbH, 2016.

Hattermann, T.: Antarctic Thermocline Dynamics along a Narrow Shelf with Easterly Winds, Journal of Physical Oceanography, 48, 2419–2443, https://doi.org/10.1175/JPO-D-18-0064.1, https://journals.ametsoc.org/view/journals/phoc/48/10/jpo-d-18-0064.1.xml, place: Boston MA, USA Publisher: American Meteorological Society, 2018.

Hattermann, T. and Levermann, A.: Response of Southern Ocean circulation to global warming may enhance basal ice shelf melting around Antarctica, Climate Dynamics, 35, 741–756, https://doi.org/10.1007/s00382-009-0643-3, https://doi.org/10.1007/s00382-009-0643-3, 2010.

Haumann, F. A., Gruber, N., and Münnich, M.: Sea-Ice Induced Southern Ocean Subsurface Warming and Surface Cooling in a Warming Climate, AGU Advances, 1, e2019AV000 132, https://doi.org/10.1029/2019AV000132, https://onlinelibrary.wiley.com/doi/abs/10.1029/2019AV000132, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2019AV000132, 2020.

Hawkins, E. and Sutton, R.: The Potential to Narrow Uncertainty in Regional Climate Predictions, Bulletin of the American Meteorological Society, 90, 1095–1108, https://doi.org/10.1175/2009BAMS2607.1, https://journals.ametsoc.org/view/journals/bams/90/8/2009bams2607_1.xml, publisher: American Meteorological Society Section: Bulletin of the American Meteorological Society, 2009.

Held, I. M., Guo, H., Adcroft, A., Dunne, J. P., Horowitz, L. W., Krasting, J., Shevliakova, E., Winton, M., Zhao, M., Bushuk, M., Wittenberg, A. T., Wyman, B., Xiang, B., Zhang, R., Anderson, W., Balaji, V., Donner, L., Dunne, K., Durachta, J., Gauthier, P. P. G., Ginoux, P., Golaz, J.-C., Griffies, S. M., Hallberg, R., Harris, L., Harrison, M., Hurlin, W., John, J., Lin, P., Lin, S.-J., Malyshev, S., Menzel, R., Milly, P. C. D., Ming, Y., Naik, V., Paynter, D., Paulot, F., Ramaswamy, V., Reichl, B., Robinson, T., Rosati, A., Seman, C., Silvers, L. G., Underwood, S., and Zadeh, N.: Structure and Performance of GFDL's CM4.0 Climate Model, Journal of Advances in Modeling Earth Systems, 11, 3691–3727, https://doi.org/https://doi.org/10.1029/2019MS001829, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS001829, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS001829, 2019.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Hellmer, H. H., Kauker, F., Timmermann, R., and Hattermann, T.: The Fate of the Southern Weddell Sea Continental Shelf in a Warming Climate, Journal of Climate, 30, 4337 – 4350, https://doi.org/10.1175/JCLI-D-16-0420.1, https://journals.ametsoc.org/view/journals/clim/30/12/jcli-d-16-0420.1.xml, place: Boston MA, USA Publisher: American Meteorological Society, 2017.

Heuzé, C.: Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models, Ocean Science, 17, 59–90, https://doi.org/10.5194/os-17-59-2021, https://os.copernicus.org/articles/17/59/2021/, publisher: Copernicus GmbH, 2021.

Juckes, M., Taylor, K. E., Durack, P. J., Lawrence, B., Mizielinski, M. S., Pamment, A., Peterschmitt, J.-Y., Rixen, M., and Sénési, S.: The CMIP6 Data Request (DREQ, version 01.00.31), Geoscientific Model Development, 13, 201–224, https://doi.org/10.5194/gmd-13-201-2020, https://gmd.copernicus.org/articles/13/201/2020/, publisher: Copernicus GmbH, 2020.

Kelley, M., Schmidt, G. A., Nazarenko, L. S., Bauer, S. E., Ruedy, R., Russell, G. L., Ackerman, A. S., Aleinov, I., Bauer, M., Bleck, R., Canuto, V., Cesana, G., Cheng, Y., Clune, T. L., Cook, B. I., Cruz, C. A., Del Genio, A. D., Elsaesser, G. S., Faluvegi, G., Kiang, N. Y., Kim, D., Lacis, A. A., Leboissetier, A., LeGrande, A. N., Lo, K. K., Marshall, J., Matthews, E. E., McDermid, S., Mezuman, K., Miller, R. L., Murray, L. T., Oinas, V., Orbe, C., García-Pando, C. P., Perlwitz, J. P., Puma, M. J., Rind, D., Romanou, A., Shindell, D. T., Sun, S., Tausnev, N., Tsigaridis, K., Tselioudis, G., Weng, E., Wu, J., and Yao, M.-S.: GISS-E2.1: Configurations and Climatology, Journal of Advances in Modeling Earth Systems, 12, e2019MS002 025, https://doi.org/10.1029/2019MS002025, https://doi.org/10.1029/2019MS002025, publisher: John Wiley & Sons, Ltd, 2020.

Khatiwala, S., Primeau, F., and Hall, T.: Reconstruction of the history of anthropogenic CO2 concentrations in the ocean, Nature, 462, 346–349, https://doi.org/10.1038/nature08526, https://www.nature.com/articles/nature08526, number: 7271 Publisher: Nature Publishing Group, 2009.

Kuhlbrodt, T., Jones, C. G., Sellar, A., Storkey, D., Blockley, E., Stringer, M., Hill, R., Graham, T., Ridley, J., Blaker, A., Calvert, D., Copsey, D., Ellis, R., Hewitt, H., Hyder, P., Ineson, S., Mulcahy, J., Siahaan, A., and Walton, J.: The Low-Resolution Version of HadGEM3 GC3.1: Development and Evaluation for Global Climate, Journal of Advances in Modeling Earth Systems, 10, 2865–2888, https://doi.org/https://doi.org/10.1029/2018MS001370, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018MS001370, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018MS001370, 2018.

Lago, V. and England, M. H.: Projected Slowdown of Antarctic Bottom Water Formation in Response to Amplified Meltwater Contributions, Journal of Climate, 32, 6319–6335, https://doi.org/10.1175/JCLI-D-18-0622.1, https://journals.ametsoc.org/view/journals/clim/32/19/jcli-d-18-0622.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2019.

Large, W. G. and Yeager, S. G.: The global climatology of an interannually varying air-sea flux data set, Climate Dyn., 33, 341–364, 2009.

Li, Q., England, M. H., Hogg, A. M., Rintoul, S. R., and Morrison, A. K.: Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater, Nature, In press, 2023a.

Li, Q., Marshall, J., Rye, C. D., Romanou, A., Rind, D., and Kelley, M.: Global Climate Impacts of Greenland and Antarctic Meltwater: A Comparative Study, Journal of Climate, In press, 2023b.

Lockwood, J. W., Griffies, C. O. D. S. M., and Winton, M.: On the role of the Antarctic Slope Front on the occurrence of the Weddell Sea polynya under climate change, Journal of Climate, 34, 2529–2548, https://doi.org/10.1175/JCLI-D-20-0069.1, 2021.

Ma, H. and Wu, L.: Global Teleconnections in Response to Freshening over the Antarctic Ocean, Journal of Climate, 24, 1071–1088, https://doi.org/10.1175/2010JCLI3634.1, https://journals.ametsoc.org/view/journals/clim/24/4/2010jcli3634.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2011.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Ma, H., Wu, L., and Li, Z.: Impact of freshening over the Southern Ocean on ENSO, Atmospheric Science Letters, 14, 28–33, https://doi.org/10.1002/asl2.410, https://onlinelibrary.wiley.com/doi/abs/10.1002/asl2.410, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/asl2.410, 2013.

Mackie, S., Smith, I. J., Ridley, J. K., Stevens, D. P., and Langhorne, P. J.: Climate Response to Increasing Antarctic Iceberg and Ice Shelf Melt, Journal of Climate, 33, 8917–8938, https://doi.org/10.1175/JCLI-D-19-0881.1, https://journals.ametsoc.org/view/journals/clim/33/20/jcliD190881.xml, publisher: American Meteorological Society Section: Journal of Climate, 2020.

Marshall, J. and Speer, K.: Closure of the meridional overturning circulation through Southern Ocean upwelling, Nature Geoscience, 5, 171–180, https://doi.org/10.1038/ngeo1391, https://www.nature.com/articles/ngeo1391, number: 3 Publisher: Nature Publishing Group, 2012.

Martin, T. and Adcroft, A.: Parameterizing the fresh-water flux from land ice to ocean with interactive icebergs in a coupled climate model, Ocean Modelling, 34, 111–124, https://doi.org/10.1016/j.ocemod.2010.05.001, https://www.sciencedirect.com/science/article/pii/S146350031000065X, 2010.

Martin, T., Park, W., and Latif, M.: Multi-centennial variability controlled by Southern Ocean convection in the Kiel Climate Model, Climate Dynamics, 40, 2005–2022, https://doi.org/10.1007/s00382-012-1586-7, https://doi.org/10.1007/s00382-012-1586-7, 2013.

Matthes, K., Biastoch, A., Wahl, S., Harlaß, J., Martin, T., Brücher, T., Drews, A., Ehlert, D., Getzlaff, K., Krüger, F., Rath, W., Scheinert, M., Schwarzkopf, F. U., Bayr, T., Schmidt, H., and Park, W.: The Flexible Ocean and Climate Infrastructure version 1 (FOCI1): mean state and variability, Geoscientific Model Development, 13, 2533–2568, https://doi.org/10.5194/gmd-13-2533-2020, https://gmd.copernicus.org/articles/13/2533/2020/, publisher: Copernicus GmbH, 2020.

Menviel, L., Timmermann, A., Timm, O. E., and Mouchet, A.: Climate and biogeochemical response to a rapid melting of the West Antarctic Ice Sheet during interglacials and implications for future climate, Paleoceanography, 25, https://doi.org/10.1029/2009PA001892, https://onlinelibrary.wiley.com/doi/abs/10.1029/2009PA001892, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2009PA001892, 2010.

Meredith, M., Sommerkorn, M., Cassotta, S., Derkson, C., Ekaykin, A., Hollowed, A., Kofinas, G., Mackintosh, A., Melbourne-Thomas, J., Muelbert, M., Ottersen, G., Pritchard, H., and Schuur, E.: Polar Regions, in: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, edited by P\"{o}rtner, H.-O., Roberts, D., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegria, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., and Weyer, N., pp. 203–320, Cambridge University Press, Cambridge, UK and New York, NY, USA, https://doi.org/10.1017/9781009157964.005, https://www.cambridge.org/core/books/ocean-and-cryosphere-in-a-changing-climate/polar-regions/8D76B8865B796C16991F7A9FB6271C2D, 2019.

Merino, N., Jourdain, N. C., Le Sommer, J., Goosse, H., Mathiot, P., and Durand, G.: Impact of increasing antarctic glacial freshwater release on regional sea-ice cover in the Southern Ocean, Ocean Modelling, 121, 76–89, https://doi.org/10.1016/j.ocemod.2017.11.009, https://www.sciencedirect.com/science/article/pii/S1463500317301956, 2018.

Mohrmann, M., Heuzé, C., and Swart, S.: Southern Ocean polynyas in CMIP6 models, The Cryosphere, 15, 4281–4313, https://doi.org/10.5194/tc-15-4281-2021, https://tc.copernicus.org/articles/15/4281/2021/, publisher: Copernicus GmbH, 2021.

Moorman, R., Morrison, A. K., and Hogg, A. M.: Thermal Responses to Antarctic Ice Shelf Melt in an Eddy-Rich Global Ocean–Sea Ice Model, Journal of Climate, 33, 6599–6620, https://doi.org/10.1175/JCLI-D-19-0846.1, https://journals.ametsoc.org/view/journals/clim/33/15/jcliD190846.xml, publisher: American Meteorological Society Section: Journal of Climate, 2020.

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6,

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Geoscientific Model Development, 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, https://gmd.copernicus.org/articles/9/3461/2016/, publisher: Copernicus GmbH, 2016.

Paolo, F. S., Fricker, H. A., and Padman, L.: Volume loss from Antarctic ice shelves is accelerating, Science, 348, 327–331, https://doi.org/10.1126/science.aaa0940, https://www.science.org/doi/abs/10.1126/science.aaa0940, _eprint: https://www.science.org/doi/pdf/10.1126/science.aaa0940, 2015.

Park, W. and Latif, M.: Ensemble global warming simulations with idealized Antarctic meltwater input, Climate Dynamics, 52, 3223–3239, https://doi.org/10.1007/s00382-018-4319-8, https://doi.org/10.1007/s00382-018-4319-8, 2019.

Pauling, A. G., Bitz, C. M., Smith, I. J., and Langhorne, P. J.: The Response of the Southern Ocean and Antarctic Sea Ice to Freshwater from Ice Shelves in an Earth System Model, Journal of Climate, 29, 1655–1672, https://doi.org/10.1175/JCLI-D-15-0501.1, https://journals.ametsoc.org/view/journals/clim/29/5/jcli-d-15-0501.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2016.

Pauling, A. G., Smith, I. J., Langhorne, P. J., and Bitz, C. M.: Time-Dependent Freshwater Input From Ice Shelves: Impacts on Antarctic Sea Ice and the Southern Ocean in an Earth System Model, Geophysical Research Letters, 44, 10,454–10,461, https://doi.org/10.1002/2017GL075017, https://onlinelibrary.wiley.com/doi/abs/10.1002/2017GL075017, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2017GL075017, 2017.

Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., van den Broeke, M. R., and Padman, L.: Antarctic ice-sheet loss driven by basal melting of ice shelves, Nature, 484, 502–505, https://doi.org/10.1038/nature10968, https://doi.org/10.1038/nature10968, 2012.

Purich, A. and England, M. H.: Historical and Future Projected Warming of Antarctic Shelf Bottom Water in CMIP6 Models, Geophysical Research Letters, 48, e2021GL092 752, https://doi.org/https://doi.org/10.1029/2021GL092752, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021GL092752, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2021GL092752, 2021.

Purich, A. and England, M. H.: Projected impacts of Antarctic meltwater anomalies over the 21st Century, Journal of Climate, In press, 2023.

Purich, A., England, M. H., Cai, W., Sullivan, A., and Durack, P. J.: Impacts of Broad-Scale Surface Freshening of the Southern Ocean in a Coupled Climate Model, Journal of Climate, 31, 2613–2632, https://doi.org/10.1175/JCLI-D-17-0092.1, https://journals.ametsoc.org/view/journals/clim/31/7/jcli-d-17-0092.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2018.

Reese, R., Gudmundsson, G. H., Levermann, A., and Winkelmann, R.: The far reach of ice-shelf thinning in Antarctica, Nature Climate Change, 8, 53–57, https://doi.org/10.1038/s41558-017-0020-x, https://doi.org/10.1038/s41558-017-0020-x, 2018.

Reintges, A., Martin, T., Latif, M., and Park, W.: Physical controls of Southern Ocean deep-convection variability in CMIP5 models and the Kiel Climate Model, Geophysical Research Letters, 44, 6951–6958, https://doi.org/https://doi.org/10.1002/2017GL074087, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL074087, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017GL074087, 2017.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B.: Ice-Shelf Melting Around Antarctica, Science, 341, 266–270, https://doi.org/10.1126/science.1235798, https://www.science.org/doi/abs/10.1126/science.1235798, _eprint: https://www.science.org/doi/pdf/10.1126/science.1235798, 2013.

Rignot, E., Mouginot, J., Scheuchl, B., van den Broeke, M., van Wessem, M. J., and Morlighem, M.: Four decades of Antarctic Ice Sheet mass balance from 1979–2017, Proceedings of the National Academy of Sciences, 116, 1095–1103, https://doi.org/10.1073/pnas.1812883116, https://www.pnas.org/doi/full/10.1073/pnas.1812883116, publisher: Proceedings of the National Academy of Sciences, 2019.

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Roemmich, D., Church, J., Gilson, J., Monselesan, D., Sutton, P., and Wijffels, S.: Unabated planetary warming and its ocean structure since 2006, Nature Climate Change, 5, 240–245, https://doi.org/10.1038/nclimate2513, https://www.nature.com/articles/nclimate2513, number: 3 Publisher: Nature Publishing Group, 2015.

Russell, J. L., Dixon, K. W., Gnanadesikan, A., Stouffer, R. J., and Toggweiler, J. R.: The Southern Hemisphere Westerlies in a Warming World: Propping Open the Door to the Deep Ocean, Journal of Climate, 19, 6382–6390, https://doi.org/10.1175/JCLI3984.1, https://journals.ametsoc.org/view/journals/clim/19/24/jcli3984.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2006.

Rye, C. D., Marshall, J., Kelley, M., Russell, G., Nazarenko, L. S., Kostov, Y., Schmidt, G. A., and Hansen, J.: Antarctic Glacial Melt as a Driver of Recent Southern Ocean Climate Trends, Geophysical Research Letters, 47, e2019GL086 892, https://doi.org/10.1029/2019GL086892, https://onlinelibrary.wiley.com/doi/abs/10.1029/2019GL086892, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2019GL086892, 2020.

Sadai, S., Condron, A., DeConto, R., and Pollard, D.: Future climate response to Antarctic Ice Sheet melt caused by anthropogenic warming, Science Advances, 6, eaaz1169, https://doi.org/10.1126/sciadv.aaz1169, https://www.science.org/doi/10.1126/sciadv.aaz1169, publisher: American Association for the Advancement of Science, 2020.

Sarmiento, J. L., Gruber, N., Brzezinski, M. A., and Dunne, J. P.: High-latitude controls of thermocline nutrients and low latitude biological productivity, Nature, 427, 56–60, https://doi.org/10.1038/nature02127, https://www.nature.com/articles/nature02127, number: 6969 Publisher: Nature Publishing Group, 2004.

Seidov, D., Barron, E., and Haupt, B. J.: Meltwater and the global ocean conveyor: northern versus southern connections, Global and Planetary Change, 30, 257–270, https://doi.org/10.1016/S0921-8181(00)00087-4, https://www.sciencedirect.com/science/article/pii/S0921818100000874, 2001.

Seland, \., Bentsen, M., Olivié, D., Toniazzo, T., Gjermundsen, A., Graff, L. S., Debernard, J. B., Gupta, A. K., He, Y.-C., Kirkevåg, A., Schwinger, J., Tjiputra, J., Aas, K. S., Bethke, I., Fan, Y., Griesfeller, J., Grini, A., Guo, C., Ilicak, M., Karset, I. H. H., Landgren, O., Liakka, J., Moseid, K. O., Nummelin, A., Spensberger, C., Tang, H., Zhang, Z., Heinze, C., Iversen, T., and Schulz, M.: Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations, Geoscientific Model Development, 13, 6165–6200, https://doi.org/10.5194/gmd-13-6165-2020, https://gmd.copernicus.org/articles/13/6165/2020/, publisher: Copernicus GmbH, 2020.

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., Agosta, C., Albrecht, T., Asay-Davis, X., Barthel, A., Calov, R., Cullather, R., Dumas, C., Galton-Fenzi, B. K., Gladstone, R., Golledge, N. R., Gregory, J. M., Greve, R., Hattermann, T., Hoffman, M. J., Humbert, A., Huybrechts, P., Jourdain, N. C., Kleiner, T., Larour, E., Leguy, G. R., Lowry, D. P., Little, C. M., Morlighem, M., Pattyn, F., Pelle, T., Price, S. F., Quiquet, A., Reese, R., Schlegel, N.-J., Shepherd, A., Simon, E., Smith, R. S., Straneo, F., Sun, S., Trusel, L. D., Van Breedam, J., van de Wal, R. S. W., Winkelmann, R., Zhao, C., Zhang, T., and Zwinger, T.: ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century, The Cryosphere, 14, 3033–3070, https://doi.org/10.5194/tc-14-3033-2020, https://tc.copernicus.org/articles/14/3033/2020/, publisher: Copernicus GmbH, 2020.

Shepherd, A., Wingham, D., Wallis, D., Giles, K., Laxon, S., and Sundal, A. V.: Recent loss of floating ice and the consequent sea level contribution, Geophysical Research Letters, 37, https://doi.org/https://doi.org/10.1029/2010GL042496, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010GL042496, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2010GL042496, 2010.

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., A, G., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V., Blazquez, A., Bonin, J., Csatho, B.,

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

Cullather, R., Felikson, D., Fettweis, X., Forsberg, R., Gallee, H., Gardner, A., Gilbert, L., Groh, A., Gunter, B., Hanna, E., Harig, C., Helm, V., Horvath, A., Horwath, M., Khan, S., Kjeldsen, K. K., Konrad, H., Langen, P., Lecavalier, B., Loomis, B., Luthcke, S., McMillan, M., Melini, D., Mernild, S., Mohajerani, Y., Moore, P., Mouginot, J., Moyano, G., Muir, A., Nagler, T., Nield, G., Nilsson, J., Noel, B., Otosaka, I., Pattle, M. E., Peltier, W. R., Pie, N., Rietbroek, R., Rott, H., Sandberg-Sørensen, L., Sasgen, I., Save, H., Scheuchl, B., Schrama, E., Schröder, L., Seo, K.-W., Simonsen, S., Slater, T., Spada, G., Sutterley, T., Talpe, M., Tarasov, L., van de Berg, W. J., van der Wal, W., van Wessem, M., Vishwakarma, B. D., Wiese, D., Wouters, B., and The IMBIE team: Mass balance of the Antarctic Ice Sheet from 1992 to 2017, Nature, 558, 219–222, https://doi.org/10.1038/s41586-018-0179-y, https://www.nature.com/articles/s41586-018-0179-y, number: 7709 Publisher: Nature Publishing Group, 2018.

Siahaan, A., Smith, R. S., Holland, P. R., Jenkins, A., Gregory, J. M., Lee, V., Mathiot, P., Payne, A. J., Ridley, J. K., and Jones, C. G.: The Antarctic contribution to 21st-century sea-level rise predicted by the UK Earth System Model with an interactive ice sheet, The Cryosphere, 16, 4053–4086, https://doi.org/10.5194/tc-16-4053-2022, https://tc.copernicus.org/articles/16/4053/2022/, 2022.

Slater, T., Lawrence, I. R., Otosaka, I. N., Shepherd, A., Gourmelen, N., Jakob, L., Tepes, P., Gilbert, L., and Nienow, P.: Review article: Earth's ice imbalance, The Cryosphere, 15, 233–246, https://doi.org/10.5194/tc-15-233-2021, https://tc.copernicus.org/articles/15/233/2021/, publisher: Copernicus GmbH, 2021.

Smith, R. S., Mathiot, P., Siahaan, A., Lee, V., Cornford, S. L., Gregory, J. M., Payne, A. J., Jenkins, A., Holland, P. R., Ridley, J. K., and Jones, C. G.: Coupling the U.K. Earth System Model to Dynamic Models of the Greenland and Antarctic Ice Sheets, Journal of Advances in Modeling Earth Systems, 13, e2021MS002 520, https://doi.org/https://doi.org/10.1029/2021MS002520, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2021MS002520, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2021MS002520, 2021.

Stewart, K., Kim, W., Urakawa, S., Hogg, A., Yeager, S., Tsujino, H., Nakano, H., Kiss, A., and Danabasoglu, G.: JRA55-do-based repeat year forcing datasets for driving ocean–sea-ice models, Ocean Modelling, 147, 101 557, 2020.

Stouffer, R. J., Seidov, D., and Haupt, B. J.: Climate Response to External Sources of Freshwater: North Atlantic versus the Southern Ocean, Journal of Climate, 20, 436–448, https://doi.org/10.1175/JCLI4015.1, https://journals.ametsoc.org/view/journals/clim/20/3/jcli4015.1.xml, publisher: American Meteorological Society Section: Journal of Climate, 2007.

Swart, N. C. and Fyfe, J. C.: The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends, Geophysical Research Letters, 40, 4328–4332, https://doi.org/10.1002/grl.50820, https://onlinelibrary.wiley.com/doi/abs/10.1002/grl.50820, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/grl.50820, 2013.

Swart, N. C., Cole, J. N. S., Kharin, V. V., Lazare, M., Scinocca, J. F., Gillett, N. P., Anstey, J., Arora, V., Christian, J. R., Hanna, S., Jiao, Y., Lee, W. G., Majaess, F., Saenko, O. A., Seiler, C., Seinen, C., Shao, A., Sigmond, M., Solheim, L., von Salzen, K., Yang, D., and Winter, B.: The Canadian Earth System Model version 5 (CanESM5.0.3), Geoscientific Model Development, 12, 4823–4873, https://doi.org/10.5194/gmd-12-4823-2019, https://gmd.copernicus.org/articles/12/4823/2019/, publisher: Copernicus GmbH, 2019.

Swingedouw, D., Fichefet, T., Goosse, H., and Loutre, M. F.: Impact of transient freshwater releases in the Southern Ocean on the AMOC and climate, Climate Dynamics, 33, 365–381, https://doi.org/10.1007/s00382-008-0496-1, https://doi.org/10.1007/s00382-008-0496-1, 2009.

Toggweiler, J. R. and Samuels, B.: Effect of drake passage on the global thermohaline circulation, Deep Sea Research Part I: Oceanographic Research Papers, 42, 477–500, https://doi.org/10.1016/0967-0637(95)00012-U, https://www.sciencedirect.com/science/article/pii/096706379500012U, 1995.

Tsujino, H., Urakawa, S., Nakano, H., Small, R. J., Kim, W. M., Yeager, S. G., Danabasoglu, G., Suzuki, T., Bamber, J. L., Bentsen, M., Böning, C. W., Bozec, A., Chassignet, E. P., Curchitser, E., Boeira Dias, F., Durack, P. J., Griffies, S. M., Harada, Y., Ilicak, M., Josey,

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023

S. A., Kobayashi, C., Kobayashi, S., Komuro, Y., Large, W. G., Le Sommer, J., Marsland, S. J., Masina, S., Scheinert, M., Tomita, H., Valdivieso, M., and Yamazaki, D.: JRA-55 based surface dataset for driving ocean–sea-ice models (JRA55-do), Ocean Modelling, 130, 79–139, 2018.

Tsujino, H., Urakawa, L. S., Griffies, S. M., Danabasoglu, G., Adcroft, A. J., Amaral, A. E., Arsouze, T., Bentsen, M., Bernardello, R., Böning, C. W., Bozec, A., Chassignet, E. P., Danilov, S., Dussin, R., Exarchou, E., Fogli, P. G., Fox-Kemper, B., Guo, C., Ilicak, M., Iovino, D., Kim, W. M., Koldunov, N., Lapin, V., Li, Y., Lin, P., Lindsay, K., Liu, H., Long, M. C., Komuro, Y., Marsland, S. J., Masina, S., Nummelin, A., Rieck, J. K., Ruprich-Robert, Y., Scheinert, M., Sicardi, V., Sidorenko, D., Suzuki, T., Tatebe, H., Wang, Q., Yeager, S. G., and Yu, Z.: Evaluation of global ocean–sea-ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2), Geoscientific Model Development, 13, 3643–3708, 2020.

van den Berk, J. and Drijfhout, S. S.: A realistic freshwater forcing protocol for ocean-coupled climate models, Ocean Modelling, 81, 36–48, https://doi.org/10.1016/j.ocemod.2014.07.003, https://www.sciencedirect.com/science/article/pii/S1463500314000833, 2014.

Weaver, A. J., Saenko, O. A., Clark, P. U., and Mitrovica, J. X.: Meltwater Pulse 1A from Antarctica as a Trigger of the Bølling-Allerød Warm Interval, Science, 299, 1709–1713, https://doi.org/10.1126/science.1081002, https://www.science.org/doi/full/10.1126/science.1081002, publisher: American Association for the Advancement of Science, 2003.

Zanowski, H. and Hallberg, R.: Weddell Polynya Transport Mechanisms in the Abyssal Ocean, Journal of Physical Oceanography, 47, 2907–2925, https://doi.org/10.1175/JPO-D-17-0091.1, 2017.

Zhang, L., Delworth, T. L., Cooke, W., and Yang, X.: Natural variability of Southern Ocean convection as a driver of observed climate trends, Nature Climate Change, 9, 59–65, https://doi.org/10.1038/s41558-018-0350-3, https://doi.org/10.1038/s41558-018-0350-3, 2019.

Ziehn, T., Chamberlain, M. A., Law, R. M., Lenton, A., Bodman, R. W., Dix, M., Stevens, L., Wang, Y.-P., Srbinovsky, J., Ziehn, T., Chamberlain, M. A., Law, R. M., Lenton, A., Bodman, R. W., Dix, M., Stevens, L., Wang, Y.-P., and Srbinovsky, J.: The Australian Earth System Model: ACCESS-ESM1.5, Journal of Southern Hemisphere Earth Systems Science, 70, 193–214, https://doi.org/10.1071/ES19035, https://www.publish.csiro.au/es/ES19035, publisher: CSIRO PUBLISHING, 2020.

Category	CMIP6 name	Units	Time	Shape	CF Standard name
Ocean 1D	zostoga	m	month	0	global_average_thermosteric_sea_level_change
Ocean 2D	mlotst	m	month	XY	ocean_mixed_layer_thickness_defined_by_sigma_t
	hfds	W/m^2	month	XY	surface_downward_heat_flux_in_sea_water
	wfo	kg/(m^2 s)	month	XY	water_flux_into_sea_water
	friver	kg/(m^2 s)	month	XYZ	water_flux_into_sea_water_from_rivers
	ficeberg	kg/(m^2 s)	month	XYZ	water_flux_into_sea_water_from_icebergs
	zos	m	month	XY	sea_surface_height_above_geoid
	msftmyz	kg/s	month	YZ-basin	ocean_meridional_overturning_mass_streamfunction
Ocean 3D	thetao	°C	month	XYZ	sea_water_potential_temperature
	so	1e-3	month	XYZ	sea_water_salinity
	uo	m/s	month	XYZ	sea_water_x_velocity
	vo	m/s	month	XYZ	sea_water_y_velocity
	wo	m/s	month	XYZ	upward_sea_water_velocity
Sea-ice 2D	siconc	%	month	XY	sea_ice_area_fraction
	sithick	m	month	XY	sea_ice_thickness
	sivol	m	month	XY	sea_ice_volume
	siu	m/s	month	XY	sea_ice_x_velocity
	siv	m/s	month	XY	sea_ice_y_velocity
	sidmassgrowthbot	kg/(m^2 s)	month	XY	tendency_of_sea_ice_amount_due_to_congelation_ice_accumulation
	sidmassmeltbot	kg/(m^2 s)	month	XY	tendency_of_sea_ice_amount_due_to_basal_melting
Atmos 2D	tas	K	month	XY	air_temperature
	pr	kg/(m^2 s)	month	XY	precipitation_flux
	psl	Pa	month	XY	air_pressure_at_mean_sea_level
	evspsbl	kg/(m^2 s)	month	XY	water_evapotranspiration_flux
	uas	m/s	month	XY	eastward_wind
	vas	m/s	month	XY	northward_wind
	clt	%	month	XY	cloud_area_fraction
Atmos 3D	ta	K	month	XY-plev19	air_temperature
	ua	m/s	month	XY-plev19	eastward_wind
	va	m/s	month	XY-plev19	eastward_wind
Static-o	areacello	m^2		XY	cell_area
	thkcello	m		XYZ	cell_thickness
	volcello	m^3		XYZ	ocean_volume
	sftof	%		XY	sea_area_fraction
Static-a	areacella	m^2		XY	cell_area
	sftlf	%		XY	land_area_fraction

Table A3. SOFIA data request. For more details see the OMIP data request specified in (Griffies et al., 2016).

https://doi.org/10.5194/egusphere-2023-198
Preprint. Discussion started: 24 March 2023