

# A Stella<sup>®</sup> version of the Arctic Mediterranean Double Estuarine Circulation model: SAMDEC v1.0

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**Abstract.** The Arctic Mediterranean can be described as a double estuarine circulation regime. This observed circulation feature, which connects the North Atlantic to the Arctic Ocean, is composed of two interconnected branches of circulation: an overturning circulation, where dense water formed in the Nordic Seas returns toward the Atlantic and an estuarine circulation, where the East Greenland Current exits the Arctic Mediterranean. A conceptual box model has previously built upon Henry Stommel's original version, concluding that a double estuarine circulation is less sensitive to perturbations in northern freshwater input than an overturning circulation in isolation. This extended model exhibits a similar freshwater sensitivity to several coupled atmosphere-ocean general circulation models (AOGCMs), which require about 1 Sv of freshwater input to induce a transition to a qualitatively weakened overturning in the Atlantic Ocean. Besides the amount of freshwater that would be required to abruptly weaken the Atlantic overturning circulation, it is essential to determine over what time scale such a transition could occur. To address this temporal aspect of potential abrupt transitions in a double estuarine circulation, we built a numerical version of the box-model in Stella<sup>®</sup>. The Stella<sup>®</sup> version of the Arctic Mediterranean Double Estuarine Circulation model (SAMDEC) is thus a new and widely-available numerical box-model representing the Arctic Mediterranean Double Estuarine Circulation and is intended to provide a numerical tool to easily solve this double estuarine theoretical framework. In addition to its simplicity of use, one of the most important added values of SAMDEC is the ability to easily determine and visualise transition times between two circulation regimes at very low computing cost, making it a valuable tool for research and education. This allows for a quantitative assessment of the response of the Arctic Mediterranean circulation to variable freshwater fluxes and temperature changes over short and long time scales. To highlight the features of SAMDEC, we showcase here two freshwater flux scenarios; 1) increased freshwater input in the Nordic Seas, which is most comparable to common 'hosing' experiments; and 2) increased freshwater input in the Nordic Seas and the Arctic. Similar to previous experiments performed with AOGCMs, the weakening caused by realistic freshwater addition is relatively slow during the first 100 years of simulation and increases thereafter. Finally, under a realistic freshwater increase, SAMDEC indicates that 88 to 176 years are needed to achieve a 15% weakening of the overturning. Overall, SAMDEC can provide insights into the dynamic of transition between circulation regimes under changes in freshwater input for both near-future and geological timescale investigations. A light version of the model can be accessed online with any internet browser and the full model can be downloaded, modified and used on a personal computer.

## 1 Introduction

The current weak state of the Atlantic meridional overturning circulation (AMOC) is an unprecedented event over the 1,500 years (Caesar et al., 2018; Rahmstorf et al., 2015; Thibodeau et al., 2018; Thornalley et al., 2018). Warming from greenhouse gases and increased high-latitude freshwater fluxes are the main potential culprits for such weakening. However, there is a high degree of uncertainty regarding the importance of each mechanism in current and future oceanographic changes. While some experiments with realistic freshwater fluxes indicate that only a small weakening of the AMOC can be attributed to freshening (Bakker et al., 2016; Swingedouw et al., 2015), others simultaneously suggest that the stability of the AMOC to freshwater input and global warming is overestimated (Liu et al., 2017). Some of this uncertainty is related to the wide range of estimated adjustment speeds in response to freshwater fluxes (Jackson and Wood, 2017; Reintges et al., 2017). For example, some studies suggest a small AMOC weakening under Greenland Ice-sheet melt by 2100, but an amplified impact by 2300 (Bakker et al., 2016). Therefore, it is critical to develop tools that can help us better constrain the response time of the thermohaline circulation (THC) to freshwater fluxes in the northern high latitudes.

The Nordic Seas are a major site for convection during winter when salty Atlantic water loses buoyancy due to heat transfer to the atmosphere (Aagaard, 1968; Helland-Hansen and Nansen, 1909; Metcalf, 1955, 1960; Mosby, 1959). This dense-water formation is a major part of the northern extension of the THC. To quantify the potential effect of change in temperature and freshwater fluxes on the THC, Stommel (1961) depicted the circulation as a two-box model where a warm surface current is cooled in the north and returned as cold, dense water. Application of this model to the north Atlantic has suggested a potential bi-stable nature of the AMOC (e.g., Bryan, 1986; Manabe and Stouffer, 1988). This concept is also commonly used to diagnose potential AMOC collapse scenarios under freshwater ‘hosing’ experiments in general circulation models, where large amounts of freshwater are added to regions of deep convection (e.g., Rahmstorf, 1996; Rahmstorf et al., 2005). However, it was recently proposed that to better understand the impact of freshwater addition, it is pertinent to consider the Arctic Mediterranean as a large-scale double estuary (Eldevik and Nilsen, 2013; Lambert et al., 2016). The warm and saline Atlantic inflow is transported to the Nordic Seas, where it cools, loses buoyancy and forms dense water that returns to the Atlantic as overflow water (e.g., Isachsen et al., 2007). However, a significant residual fraction of the densified inflow travels to the Arctic Ocean where it freshens and gains buoyancy. This fresh and cold water exits the Arctic Mediterranean via the East Greenland Current and the Canadian Arctic Archipelago (Rudels, 1989). Taken together, these different transport branches form a double estuarine circulation (Rudels, 2010; Stigebrandt, 1985). Interestingly, it was previously demonstrated that the strength of the North Atlantic THC is less sensitive to high-latitude freshwater input when considering the Arctic-Atlantic thermohaline circulation as a double estuary (Eldevik and Nilsen, 2013; Lambert et al., 2016). This relative insensitivity contrasts with Stommel’s original model (1961) and some general circulation models (e.g., Rahmstorf, 1996; Rahmstorf et al., 2005), but seems to be in agreement with most coupled atmosphere-ocean general circulation models (AOGCMs) that show a relatively weaker sensitivity to freshwater input (e.g., Bakker et al., 2016; Gregory et al., 2005; Weaver et al., 2012). According to the latter models, an addition of 1 Sverdrup (Sv) of freshwater induced by deliberate water-hosing experiments is required to shut down the overturning circulation (Stouffer et al., 2006). The sensitivity of the THC to freshwater flux inferred from Stommel’s representation might be overestimated due to the absence of the East Greenland Current estuarine branch (Guan and Huang, 2008; Longworth et al., 2005; Nilsson and Walin, 2001).

In this paper, we describe the Stella<sup>®</sup> version of the double estuarine circulation model (SAMDEC), which numerically solves the box-model of Lambert et al. (2016). SAMDEC facilitates the investigation of the model’s transition speed between different circulation regimes under freshwater variations. To illustrate its use for purposes of research and education we present some basic results of SAMDEC by focusing on transition rates due to realistic increases in northern freshwater input.

## 2 Model description

### 2.1 A numerical box model

A numerical tool (SAMDEC) was constructed using Stella<sup>®</sup> (v. Architect 1.4.3). The model is composed of two main modules; the water circulation (or water transport) module and the salt conservation module, which interact with each other. This model allows for three stable double estuarine circulation regimes, namely, 1) a thermal regime, similar to the present-day Arctic Mediterranean, with a surface inflow from the Atlantic which returns partly as dense, and partly as light water, 2) a haline regime, where the Arctic Mediterranean is covered with cold, fresh surface waters and the overturning branch is reversed, and 3) a throughflow regime, where the overturning branch is reversed, but the estuarine branch is strong enough to sustain a warm inflow at depth and along the surface, allowing for relatively warm surface waters in the Nordic Seas (Fig 1). This model comes with the same assumptions of previous models built on the same principle, which include: 1) constant temperature, 2) closed freshwater cycle, 3) well-mixed basins, 4) constant basin volumes, and 5) a linear scaling between density differences and volumes of water transported between basins (Stommel, 1961; Lambert et al., 2016). These assumptions and their respective caveats have been extensively discussed and will not be repeated here (e.g. De Boer et al., 2010; Griesel and Maqueda, 2006; Guan and Huang, 2008; Kuhlbrodt et al., 2007; Marotzke, 2000; Nilsson and Walin, 2001; Rudels, 2012, 2010; Toggweiler and Samuels, 1995; Werenskiold, 1935). Hence, the box-model of Lambert et al. (2016) was not designed to produce a fully realistic description of the thermohaline circulation in the Arctic Mediterranean, but to illustrate the dynamics and freshwater-sensitivity of a double estuarine circulation. With SAMDEC, we aim to expand the analysis of such a system by resolving its transient behavior induced by freshwater perturbations. In the remainder of this section, we briefly describe the model equations, but for a full description the reader is referred to Lambert et al. (2016) and references therein.

### 2.2 Salt conservation

The dynamical equations governing the box model are based on salt conservation in each basin. The processes which exchange salt between the basins are advection through volume exchange and a closed freshwater cycle:

$$V_1 \frac{dS_1}{dt} = -\frac{1}{2} (\Psi_E + |\Psi_O| + |\Psi_I|) \Delta S_{12} - \Psi_E \Delta S_{23} + F_2 + F_3 \quad (1)$$

$$V_2 \frac{dS_2}{dt} = \frac{1}{2} (\Psi_E + |\Psi_O| + |\Psi_I|) \Delta S_{12} - F_2 \quad (2)$$

$$V_3 \frac{dS_3}{dt} = \Psi_E \Delta S_{23} - F_3 \quad (3)$$

where  $F_i$  represents the freshwater input in a selected basin,  $\Psi_E$  is the strength of the estuarine circulation,  $\Psi_O$  is the strength of the overturning circulation,  $\Psi_I$  is the surface exchange between the North Atlantic and Nordic Seas and  $V_i$  is the volume of the basin. Note that freshwater input is expressed as virtual salinity fluxes. In order to ensure a closed freshwater cycle, the addition of freshwater to the cold basins 2 and 3 (Nordic Seas and Arctic) is compensated by freshwater removal (evaporation) from the warm Atlantic basin 1 (Fig 1).

### 2.3 Water circulation

The volume fluxes between the North Atlantic and the Nordic Seas can flow in both direction; e.g., the modern-day situation, the thermal circulation, is characterized by a positive North Atlantic inflow that indicates surface water flowing from the North Atlantic toward the Nordic Seas and a positive overturning, representing deep water flowing from the Nordic Seas toward the North Atlantic. Following Stommel (1961), the flow of the overturning circulation is scaled linearly to the density contrast between the North Atlantic and the Nordic Seas:

$$\Psi_O = k_O \frac{\rho_2 - \rho_1}{\rho_{\text{ref}}} = k_O (\alpha \Delta T_{12} - \beta \Delta S_{12}) \quad (4)$$

where  $\rho_i$  is the density of each basin, and  $\rho_{\text{ref}}$  is a reference density. Assuming a linear equation of state,  $\alpha$  and  $\beta$  are the thermal and haline expansion coefficients,  $\Delta T_{12}$  is the temperature difference between the North Atlantic and the other basins, and  $\Delta S_{12}$  is the salinity difference between basins 1 and 2 and  $k_o$  is a hydraulic constant that links the overturning flux to the density contrast.

The volume transport through the estuarine circulation is similarly scaled to the density contrast between basins 2 and 3. By assuming an identical temperature for both basins, the transport is merely determined by the salinity contrast between the Nordic Seas and the Arctic:

$$\Psi_E = k_E \frac{\rho_2 - \rho_3}{\rho_{\text{ref}}} = k_E (\beta \Delta S_{23}) \quad (5)$$

where  $k_E$  is the hydraulic constant for the estuarine circulation.

The set of equations is closed by assuming volume conservation:

$$\Psi_I = \Psi_E + \Psi_O \quad (6)$$

## 2.4 Time integration

The model computes the flow of water between each basin in Sv (1 Sv =  $10^6$  m<sup>3</sup>/s) based on the salinity and temperature gradient. The user can define the time unit used in the model and the delta time (DT). The DT is defined as the number of times the numerical values are recalculated per time unit. Here, we used a time unit of one-year for short simulations and twenty years for the longer simulations, with a DT of 12 (monthly) and 20 (yearly) respectively. While a high value of DT should yield a higher precision, sensitivity testing suggests no different between a value of 1 and 1000, suggesting that the values calculated by SAMDEC are stable over each time unit. The equations are solved using Euler's method; briefly the model computes the values for flows and converters and then estimates the ensuing change in corresponding reservoirs over the interval DT. During the iteration process, the model recalculates new values for flows and converters and then again calculates the changes in corresponding reservoirs over the next interval DT

## 3 Model parameters and modern calibration

### 3.1 Basin volumes

The water transport module is composed of three basins, 1) North Atlantic water above the thermocline, 2) the Nordic Seas dense water and 3) water above the Arctic Ocean halocline. Each of these basins are linked to each other by water fluxes named North Atlantic Inflow, Overturning and Polar Outflow. The basin surface area estimate for the North Atlantic is based on a 1 arc-minute digital representation of Earth's solid surface that integrates land topography and ocean bathymetry from numerous global and regional data (Amante and Eakins, 2009; Eakins and Sharman, 2010). To perform our calibration, we defined the North Atlantic thermocline as the upper 600 m, while the Arctic halocline was defined as the upper 200 m of the Arctic Ocean. The volume of the Arctic was thus calculated by multiplying the non-shelves area ( $4,508,000$  km<sup>2</sup>) by 200 m (Stein, 2008). The volume of the Nordic Seas was estimated using a surface extent of  $2.5 \times 10^6$  km<sup>2</sup> and a maximum convection of 1.5 km (Drange et al., 2013; Latarius and Quadfase, 2016). While it is not clear how much of the water below the Greenland-Scotland Ridge is actively contributing to the circulation, here we use the maximum depth of convection, which should translate into an upper limit for the transition speed.

### 3.2 Forcing parameters

All parameters are fully and easily configurable by the user in the full version of the model. Here, we present the parameters we used and assumed to be the most relevant for modelling the modern oceanography of this region. The hydraulic constants were calculated using equations 1 and 2 to yield an overturning and a polar outflow equivalent to present-day estimates (i.e., 6.0 Sv for the overturning and 2.5 Sv for the estuarine branch). We initialized the model with  $F_2$  and  $F_3$  resembling present-day water transport and salinity. Freshwater fluxes needed to keep salinity constant at four digits precision in all basins for a duration of 20,000 years were found to be:  $F_2 = 2.55$  and  $F_3 = 2.25$ . In this configuration,  $F_2$  and  $F_3$  are virtual salinity fluxes (freshwater flux  $\times$  reference salinity) and are therefore required to be normalized by 35.2 in order to estimate the equivalence in Sv. This yields modern day fluxes of 72.44 and 63.93 mSv in the Nordic Seas and the upper Arctic (Fig 2).

**Table 1: Initial parameters of SAMDEC v1.0.**

<i>Initial Parameters</i>	<i>Values</i>
<i>Hydraulic constant overturning</i>	10 714 Sv
<i>Hydraulic constant estuarine</i>	3 472 Sv
<i>Haline contraction coefficient</i>	$8 \times 10^{-4} \text{ psu}^{-1}$
<i>Thermal expansion coefficient</i>	$10^{-4} \text{ K}^{-1}$
<i>Freshwater in the Nordic Seas</i>	72 mSv
<i>Freshwater in the Arctic</i>	64 mSv
<i>North Atlantic thermocline</i>	$2.489 \times 10^{16} \text{ km}^3$
<i>Nordic Seas</i>	$3.75 \times 10^{15} \text{ km}^3$
<i>Arctic halocline</i>	$9.018 \times 10^{14} \text{ km}^3$
<i>North Atlantic Salinity (<math>S_1</math>)</i>	35.2
<i>Nordic Seas Salinity (<math>S_2</math>)</i>	34.9
<i>Arctic Halocline Salinity (<math>S_3</math>)</i>	34

## 4 Evaluation of the model sensitivity to freshwater input

### 4.1 Stability and transition speed under constant freshwater forcing

To evaluate the performance of SAMDEC, we reproduced the calculations performed within the theoretical framework and presented in Lambert et al (2016). We evaluated the stability and transition speed of thermohaline circulation in the North Atlantic under two scenarios: 1) an increase of freshwater in the Nordic Seas only and, 2) a simultaneous and equal increase of the freshwater flux in both the Nordic Seas and the Arctic. In scenario 1, the overturning reaches zero if a total of 102 mSv of freshwater is added in the Nordic Seas (+ 30 mSv compared to steady-state). This freshwater input is just enough to destabilize the circulation, and a transition to the haline regime occurs after approximately 5,000 years (Fig 2a). The transition is much quicker (less than 2,700 years) if the freshwater input in the Nordic Seas reaches 103 mSv (+ 31 mSv compared to steady state). To induce a transition in less than 50 years, a much larger input is required (0.4 Sv; Fig 2b). An addition of 0.1 Sv weakens the overturning branch by 43% within 100 years. This is a stronger weakening compared to the inter-model comparison experiment that found a 30% weakening under the same freshwater forcing (Stouffer et al., 2006).

In scenario 2, the freshwater fluxes increase equally in both basins and the overturning reaches zero after a total addition of 87 mSv over 8,740 years compared to steady-state (Fig 2c). The circulation then transitions into a throughflow circulation, with a very weak North Atlantic surface inflow (0.9 Sv) into the Nordic Seas (not shown). Interestingly, in this

scenario the circulation quickly transitions from the throughflow (positive Atlantic inflow and negative overturning) regime to the haline regime (negative Atlantic inflow and overturning) if both freshwater inputs further increase proportionally. Under an addition of 0.1 Sv equally distributed between the Nordic Seas and the Arctic over a 100-year period, the overturning weakens by 19 % (Fig 2d). However, under a total addition of 1 Sv, the overturning reaches zero in less than 50 years. A major difference between the two scenarios is in the strength of the Atlantic inflow, which is more resilient in scenario 2. This is due to the strength of the Polar outflow that is maintained by the constant addition of freshwater in the Arctic halocline and is similar to the results of the inter-AOGCM model comparison experiment of Stouffer et al. (2006), which found that the Atlantic overturning would reach zero within 50 years under a 1.0 Sv freshwater addition. For a total addition of 0.1 Sv, the overturning will be reduced by about 1 Sv if 30% of this freshwater input is added to the Nordic Seas but it will reach zero within about 300 years if 80% of the freshwater is released in the Nordic Seas (Fig 3a). In large freshwater flux experiments, the localisation does not necessarily prevent the transition of the overturning but delays and minimises it (Fig 3b) by maintaining a strong North Atlantic inflow (Fig 3c).

These results are in general agreement with the theoretical solutions of Lambert et al. (2016) that estimated a freshwater increase of 37 mSv (scenario 1; SAMDEC = 30 mSv) or 123 mSv (scenario 2; SAMDEC = 87 mSv) is necessary to destabilise the thermal circulation. The theoretical solution used a linear stability analysis to determine if a circulation state can reside in equilibrium, while we defined a circulation that is not at equilibrium as a circulation where the overturning reached 0 within the period of the simulation and thus it might contribute to the small difference between the numerical and analytical solutions.

#### 4.2 Stability and transition speed under increasing freshwater forcing

Increased precipitation, runoff and loss of sea-ice contributed to an increased flux of freshwater into the Arctic Ocean during the last decades at a rate of about 0.1 mSv yr<sup>-1</sup> (Haine et al., 2015). It is also projected that the freshwater flux will continue to increase during the next century at a rate of about 0.05 mSv yr<sup>-1</sup> (reviewed in Haine et al., 2015). Here we tested the effect of such rates on the overturning cell with SAMDEC using different partitioning of the freshwater flux (Fig 4). While higher fluxes of freshwater tend to reduce the overturning more rapidly, the partitioning of the flux between the Arctic and the Nordic Seas is crucial in estimating the timing of the transition in circulation regime. As an example, the overturning reaches zero in about 300 years under an increased flux of 0.05 mSv yr<sup>-1</sup> if 90% of the freshwater is directed into the Nordic Seas, while the overturning reaches zero after 800 years under the same total freshwater input if only 30% is directed into the Nordic Seas (Fig 4). Interestingly, in both experiments the initial weakening is slow and increases after 200 to 300 years of freshwater addition, very much in line with previous results from coupled-AOGCMs (Bakker et al., 2016). Under the scenarios investigated here (0.1 and 0.05 mSv yr<sup>-1</sup>), SAMDEC estimates that it would take respectively 88 to 176 years and 128 to 283 years for the overturning to weaken by 15%, depending on the location of the freshwater input (Fig 4). This is slightly longer than, but in the same order of magnitude, as what was estimated by Caesar et al. (2018), who proposed that the AMOC weakened by about 15% since the mid-twentieth century. This longer time response might indicate that, while freshwater is playing a role in the ongoing weakening of the AMOC, other factors such as thermal and wind forcing are probably also contributing (e.g., Bakker et al., 2016).

#### 4.3 Weakening and recovery transition speed under a 250-year freshwater addition

We investigated the weakening rate under a 250-year freshwater addition and the recovery rate during the 750 following years. We applied a freshwater forcing of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 or 1 Sv to make our experimental design comparable to the inter-AOGCM model comparison of Jackson and Wood (2017). We tested these fluxes only with the configuration of scenario 2, freshwater forcing evenly split between the Nordic Seas and the Arctic Ocean. The forcing was

defined as the freshwater added to the equilibrium state (i.e., 72.44 and 63.93 mSv in the Nordic Seas and the upper Arctic respectively). In all cases the response is asymmetric, but the recovery is different depending on the intensity of freshwater input (Fig 5). The overturning recovers close to its initial value within the 750 years of recovery only if the overturning did not reach zero (Fig 5). In the experiments where the overturning reached zero, the overturning strength increased back fairly quickly but then reached a new equilibrium in the throughflow circulation mode (i.e., negative overturning and positive Atlantic inflow). Interestingly, we do not see an overshoot in the overturning right after the recovery as in a recent experiment with a coupled model (Haskins et al., 2018). This supports the hypothesis that the overshoot is created by density change in the South Atlantic, which is not accounted for in this box model.

## 5 Conclusion

SAMDEC provides a simple and user-friendly framework to investigate the impact of freshwater input on the northernmost extension of the North Atlantic thermohaline circulation. Evaluation of the numerical solutions in SAMDEC against the analytical solutions revealed a good agreement with regard to freshwater fluxes needed to destabilise the overturning circulation. Moreover, the modeled amount of freshwater input needed to quickly weaken the overturning circulation is similar to what was found using coupled atmosphere-ocean general circulation models, which suggests this model provides a reliable estimation for the temporal response of thermohaline circulation to changes in freshwater forcing. In addition to its user friendliness, the model allows for a mechanistic evaluation of the impact of increased freshwater input on thermohaline circulation through time, which is difficult to achieve analytically. Therefore, SAMDEC provides a robust framework to test the response of thermohaline circulation between the North Atlantic and the Arctic Ocean to changes in freshwater forcing which has possibly played a role in observed temperature and/or salinity gradients in the past (e.g., Bauch et al., 2012; Doherty and Thibodeau, 2018; Kandiano et al., 2016; Thibodeau et al., 2017), as well as in future projections (e.g., IPCC, 2013).

## 6 Code and model availability

A browser version of the model is available at: <https://exchange.iseesystems.com/public/benoit-thibodeau/samdec>.

The full model can be downloaded at: <https://exchange.iseesystems.com/directory/benoit-thibodeau>. The *isee systems* software Stella® is required to run the full model. The complete equations used in the model are available on BT personal website (<http://web.hku.hk/~bthib/samdec>)

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## References

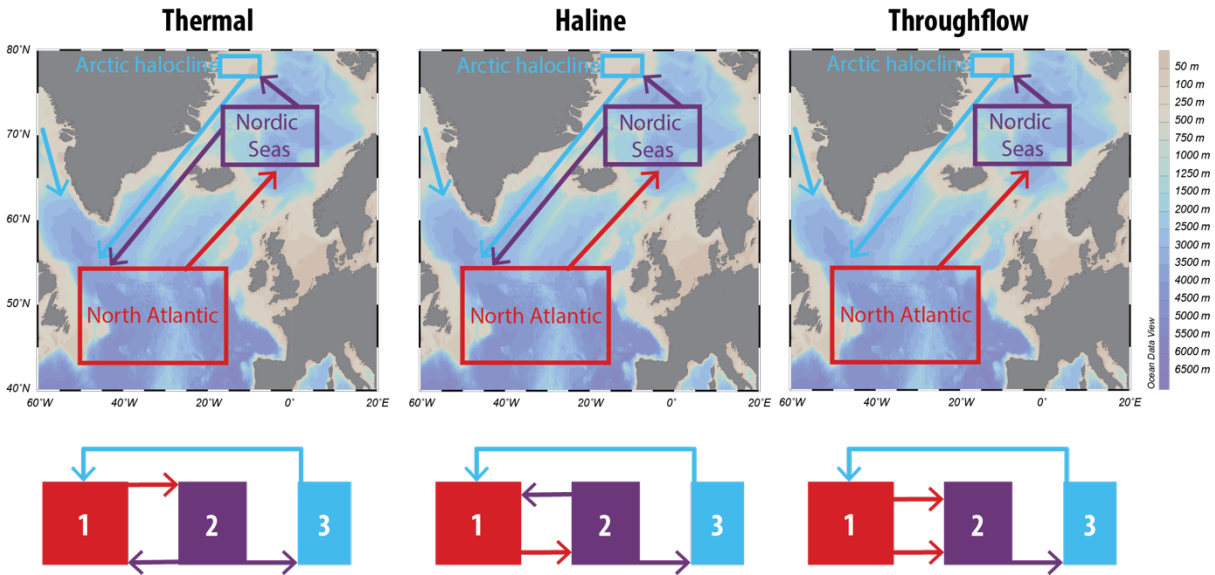
- Aagaard, K.: Temperature variations in the Greenland Sea deep-water, *Deep. Res. Oceanogr. Abstr.*, 15(3), 281–296, doi:10.1016/0011-7471(68)90006-5, 1968.
- Amante, C. and Eakins, B. W.: ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis., 2009.
- 5 Bakker, P., Schmittner, A., Lenaerts, J. T. M., Abe-Ouchi, A., Bi, D., van den Broeke, M. R., Chan, W. L., Hu, A., Beadling, R. L., Marsland, S. J., Mernild, S. H., Saenko, O. A., Swingedouw, D., Sullivan, A. and Yin, J.: Fate of the Atlantic Meridional Overturning Circulation: Strong decline under continued warming and Greenland melting, *Geophys. Res. Lett.*, 43(23), 12,252–12,260, doi:10.1002/2016GL070457, 2016.
- Bauch, H. A., Kandiano, E. S. and Helmke, J. P.: Contrasting ocean changes between the subpolar and polar North Atlantic during the past 135 ka, *Geophys. Res. Lett.*, 39(11), doi:10.1029/2012GL051800, 2012.
- 10 De Boer, A. M., Gnanadesikan, A., Edwards, N. R. and Watson, A. J.: Meridional density gradients do not control the Atlantic overturning circulation, *J. Phys. Oceanogr.*, 40(2), 368–380, doi:10.1175/2009JPO4200.1, 2010.
- Bryan, F.: High-latitude salinity effects and interhemispheric thermohaline circulations, *Nature*, 323(6086), 301–304, doi:10.1038/323301a0, 1986.
- 15 Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. and Saba, V.: Observed fingerprint of a weakening Atlantic Ocean overturning circulation, *Nature*, 556(7700), 191–196, doi:10.1038/s41586-018-0006-5, 2018.
- Doherty, J. M. and Thibodeau, B.: Cold Water in a Warm World: Investigating the Origin of the Nordic Seas' Unique Surface Properties During MIS 11, *Front. Mar. Sci.*, 5, 251, doi:10.3389/fmars.2018.00251, 2018.
- Drange, H., Dokken, T., Furevik, T., Gerdes, R., Berger, W., Nesje, A., Orvik, K. A., Skagseth, Ø., Skjelvan, I. and Østerhus, S.: The Nordic Seas: An Overview, in *The Nordic Seas: An Integrated Perspective: Oceanography, Climatology, Biogeochemistry, and Modeling*, pp. 1–10., 2013.
- 20 Eakins, B. W. and Sharman, G. F.: Volumes of the World's Oceans from ETOPO1, NOAA Natl. Geophys. Data Cent. [online] Available from: [https://ngdc.noaa.gov/mgg/global/etopo1\\_ocean\\_volumes.html](https://ngdc.noaa.gov/mgg/global/etopo1_ocean_volumes.html) (Accessed 3 February 2019), 2010.
- Eldevik, T. and Nilsen, J. E. Ø.: The arctic-atlantic thermohaline circulation, *J. Clim.*, 26(21), 8698–8705, doi:10.1175/JCLI-D-13-00305.1, 2013.
- 25 Gregory, J. M., Dixon, K. W., Stouffer, R. J., Weaver, A. J., Driesschaert, E., Eby, M., Fichefet, T., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Sokolov, A. P. and Thorpe, R. B.: A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO<sub>2</sub> concentration, *Geophys. Res. Lett.*, 32(12), 1–5, doi:10.1029/2005GL023209, 2005.
- 30 Griesel, A. and Maqueda, M. A. M.: The relation of meridional pressure gradients to North Atlantic deep water volume transport in an ocean general circulation model, *Clim. Dyn.*, 26(7–8), 781–799, doi:10.1007/s00382-006-0122-z, 2006.
- Guan, Y. P. and Huang, R. X.: Stommel's box model of thermohaline circulation revisited - The role of mechanical energy supporting mixing and the wind-driven gyration, *J. Phys. Oceanogr.*, 38(4), 909–917, doi:10.1175/2007JPO3535.1, 2008.
- Haine, T. W. N., Curry, B., Gerdes, R., Hansen, E., Karcher, M., Lee, C., Rudels, B., Spreen, G., de Steur, L., Stewart, K. D. and Woodgate, R.: Arctic freshwater export: Status, mechanisms, and prospects, *Glob. Planet. Change*, 125, 13–35, doi:10.1016/j.gloplacha.2014.11.013, 2015.
- 35 Haskins, R. K., Oliver, K. I. C., Jackson, L. C., Drijfhout, S. S. and Wood, R. A.: Explaining asymmetry between weakening and recovery of the AMOC in a coupled climate model, *Clim. Dyn.*, 1–13, doi:10.1007/s00382-018-4570-z, 2018.
- Helland-Hansen, B. and Nansen, F.: The Norwegian Sea, *Rep. Nor. Fish. Mar. Investig.*, 2(2), 1–360, 1909.
- 40 IPCC: Climate Change 2013: The Physical Science Basis. Summary for Policymakers. [online] Available from: <http://medcontent.metapress.com/index/A65RM03P4874243N.pdf>, 2013.
- Isachsen, P. E., Mauritzen, C. and Svendsen, H.: Dense water formation in the Nordic Seas diagnosed from sea surface buoyancy fluxes, *Deep. Res. Part I Oceanogr. Res. Pap.*, 54(1), 22–41, doi:10.1016/j.dsr.2006.09.008, 2007.



- Jackson, L. C. and Wood, R. A.: Timescales of AMOC decline in response to fresh water forcing, *Clim. Dyn.*, 0(0), 1–18, doi:10.1007/s00382-017-3957-6, 2017.
- Kandiano, E. S., van der Meer, M. T. J., Bauch, H. A., Helmke, J., Damste, J. S. S. and Schouten, S.: A cold and fresh ocean surface in the Nordic Seas during MIS 11: Significance for the future ocean, *Geophys. Res. Lett.*, 43(20), 10,929–10,937, doi:10.1002/2016GL070294, 2016.
- 5 Kuhlbrodt, T., Griesel, A., Montoya, M., Levermann, A., Hofmann, M. and Rahmstorf, S.: On the driving processes of the Atlantic meridional overturning circulation, *Rev. Geophys.*, 45(2), RG2001, doi:10.1029/2004RG000166, 2007.
- Lambert, E., Eldevik, T. and Haugan, P. M.: How northern freshwater input can stabilise thermohaline circulation, *Tellus, Ser. A Dyn. Meteorol. Oceanogr.*, 68(1), doi:10.3402/tellusa.v68.31051, 2016.
- 10 Latarius, K. and Quadfasel, D.: Water mass transformation in the deep basins of the Nordic Seas: Analyses of heat and freshwater budgets, *Deep. Res. Part I Oceanogr. Res. Pap.*, 114, 23–42, doi:10.1016/j.dsr.2016.04.012, 2016.
- Liu, W., Xie, S.-P., Liu, Z. and Zhu, J.: Overlooked possibility of a collapsed Atlantic Meridional Overturning Circulation in warming climate, *Sci. Adv.*, 3(1) [online] Available from: <http://advances.sciencemag.org/content/3/1/e1601666.abstract>, 2017.
- 15 Longworth, H., Marotzke, J. and Stocker, T. F.: Ocean gyres and abrupt change in the thermohaline circulation: A conceptual analysis, *J. Clim.*, 18(13), 2403–2416, doi:10.1175/JCLI3397.1, 2005.
- Manabe, S. and Stouffer, R. J.: Two stable equilibria of a coupled ocean-atmosphere model, *J. Clim.*, 1, 841–866, 1988.
- Marotzke, J.: Abrupt climate change and thermohaline circulation: Mechanisms and predictability, *Proc. Natl. Acad. Sci. U. S. A.*, 97(4), 1347–1350, doi:10.1073/pnas.97.4.1347, 2000.
- 20 Metcalf, W. G.: On the formation of bottom water in the Norwegian Basin, *Eos, Trans. Am. Geophys. Union*, 36(4), 596–600, doi:10.1029/TR036i004p00596, 1955.
- Metcalf, W. G.: A note on water movement in the Greenland-Norwegian Sea, *Deep Sea Res.*, 7(3), 190–200, doi:10.1016/0146-6313(60)90025-3, 1960.
- Mosby, H.: Deep water in the Norwegian Sea, *Geofis. Publ.*, 21(3), 1959.
- 25 Nilsson, J. and Walin, G.: Freshwater forcing as a booster of thermohaline circulation, *Tellus, Ser. A Dyn. Meteorol. Oceanogr.*, 53(5), 629–641, doi:10.3402/tellusa.v53i5.12232, 2001.
- Rahmstorf, S.: On the freshwater forcing and transport of the Atlantic thermohaline circulation, *Clim. Dyn.*, 12(12), 799–811, doi:10.1007/s003820050144, 1996.
- Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S. and Schaffernicht, E. J.: Exceptional  
30 twentieth-century slowdown in Atlantic Ocean overturning circulation, *Nat. Clim. Chang.*, 5(5), 475–480, doi:10.1038/nclimate2554, 2015.
- Rahmstorf, S., Crucifix, M., Ganopolski, A., Goosse, H., Kamenkovich, I., Knutti, R., Lohmann, G., Marsh, R., Myzak, L. A., Wang, Z. M., Weaver, A. J. J., Rahmstorf, S., Crucifix, M., Ganopolski, A., Goosse, H., Kamenkovich, I., Knutti, R., Lohmann, G., Marsh, R., Mysak, L. a., Wang, Z. M. and Weaver, A. J. J.: Thermohaline circulation hysteresis: A model intercomparison,  
35 *Geophys. Res. Lett.*, 32(23), 1–5, doi:10.1029/2005GL023655, 2005.
- Reintges, A., Martin, T., Latif, M. and Keenlyside, N. S.: Uncertainty in twenty-first century projections of the Atlantic Meridional Overturning Circulation in CMIP3 and CMIP5 models, *Clim. Dyn.*, 49(5–6), 1495–1511, doi:10.1007/s00382-016-3180-x, 2017.
- Rudels, B.: The formation of polar surface water, the ice export and the exchanges through the Fram Strait, *Prog. Oceanogr.*,  
40 22(3), 205–248, doi:10.1016/0079-6611(89)90013-X, 1989.
- Rudels, B.: Constraints on exchanges in the Arctic Mediterranean - do they exist and can they be of use?, *Tellus, Ser. A Dyn. Meteorol. Oceanogr.*, 62(2), 109–122, doi:10.1111/j.1600-0870.2009.00425.x, 2010.
- Rudels, B.: Arctic Ocean circulation and variability - Advection and external forcing encounter constraints and local processes,

- Ocean Sci., 8(2), 261–286, doi:10.5194/os-8-261-2012, 2012.
- Stein, R.: Arctic Ocean Sediments: Processes, Proxies, and Paleoenvironment, edited by H. Chamley, Elsevier, Amsterdam, The Netherlands., 2008.
- Stigebrandt, A.: On the hydrographic and ice conditions in the northern North Atlantic during different phases of a glaciation cycle, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 50(2–3), 303–321, doi:10.1016/0031-0182(85)90074-4, 1985.
- 5 Stommel, H.: Thermohaline Convection with Two Stable Regimes of Flow, *Tellus*, 13(2), 224–230, doi:10.3402/tellusa.v13i2.9491, 1961.
- Stouffer, R. J., Yin, J., Gregory, J. M., Dixon, K. W., Spelman, M. J., Hurlin, W., Weaver, A. J., Eby, M., Flato, G. M., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Peltier, W. R., Robitaille, D. Y., Sokolov, A., Vettoretti, G. and Weber, S. L.: Investigating the Causes of the Response of the Thermohaline Circulation to Past and Future Climate Changes, *J. Clim.*, 19(8), 1365–1387, doi:10.1175/JCLI3689.1, 2006.
- 10 Swingedouw, D., Rodehacke, C. B., Olsen, S. M., Menary, M., Gao, Y., Mikolajewicz, U. and Mignot, J.: On the reduced sensitivity of the Atlantic overturning to Greenland ice sheet melting in projections: a multi-model assessment, *Clim. Dyn.*, 44(11–12), 3261–3279, doi:10.1007/s00382-014-2270-x, 2015.
- 15 Thibodeau, B., Bauch, H. A. and Pedersen, T. F.: Stratification-induced variations in nutrient utilization in the Polar North Atlantic during past interglacials, *Earth Planet. Sci. Lett.*, 457, 127–135, doi:10.1016/j.epsl.2016.09.060, 2017.
- Thibodeau, B., Not, C., Zhu, J., Schmittner, A., Noone, D., Tabor, C., Zhang, J. and Liu, Z.: Last Century Warming Over the Canadian Atlantic Shelves Linked to Weak Atlantic Meridional Overturning Circulation, *Geophys. Res. Lett.*, 45(22), 12,376–12,385, doi:10.1029/2018GL080083, 2018.
- 20 Thornalley, D. J. R., Oppo, D. W., Ortega, P., Robson, J. I., Brierley, C. M., Davis, R., Hall, I. R., Moffa-Sanchez, P., Rose, N. L., Spooner, P. T., Yashayaev, I. and Keigwin, L. D.: Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years, *Nature*, 556(7700), 227–230, doi:10.1038/s41586-018-0007-4, 2018.
- Toggweiler, J. R. and Samuels, B.: Effect of drake passage on the global thermohaline circulation, *Deep. Res. Part I*, 42(4), 477–500, doi:10.1016/0967-0637(95)00012-U, 1995.
- 25 Weaver, A. J., Sedláček, J., Eby, M., Alexander, K., Cressin, E., Fichefet, T., Philippon-Berthier, G., Joos, F., Kawamiya, M., Matsumoto, K., Steinacher, M., Tachiiri, K., Tokos, K., Yoshimori, M., Zickfeld, K., Kawamiy, M., Matsumoto, K., Steinacher, M., Tachiiri, K., Tokos, K., Yoshimori, M. and Zickfeld, K.: Stability of the Atlantic meridional overturning circulation: A model intercomparison, *Geophys. Res. Lett.*, 39(20), n/a-n/a, doi:10.1029/2012GL053763, 2012.
- Werenskiold, W.: Coastal currents, *Geophys. Publ*, 10(13), 1–14, 1935.

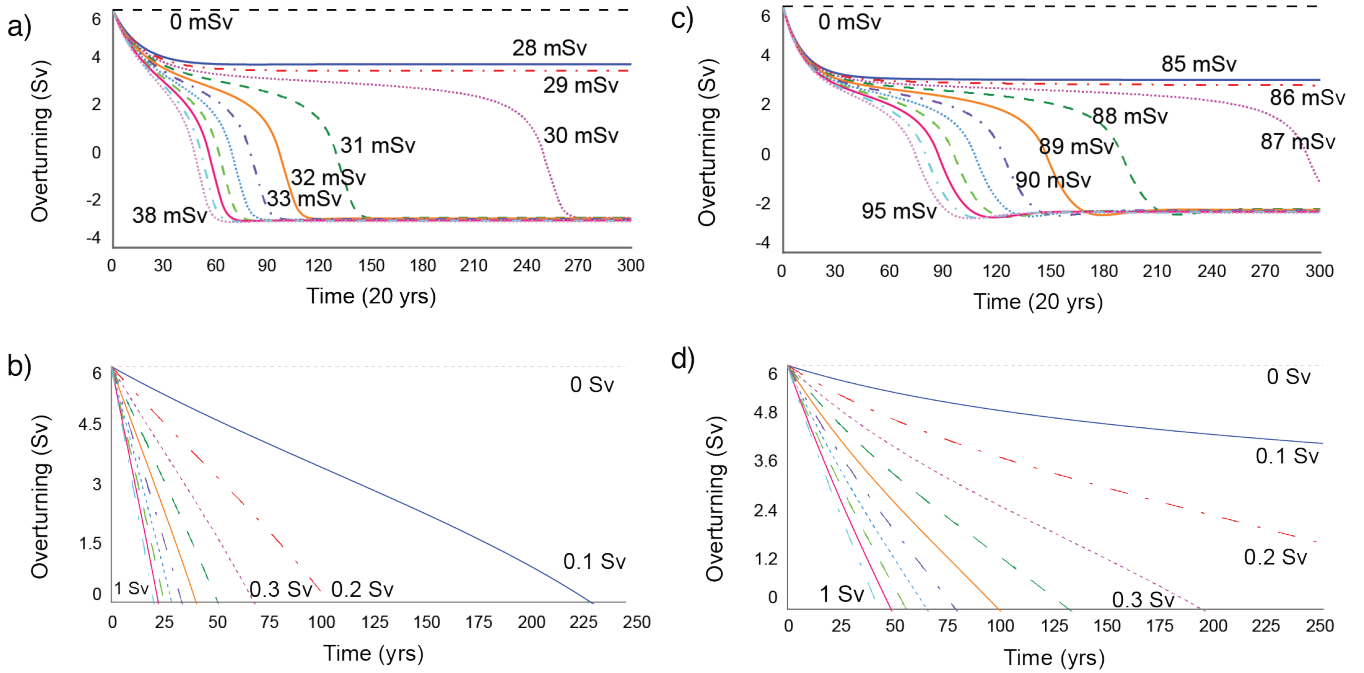
## Figures



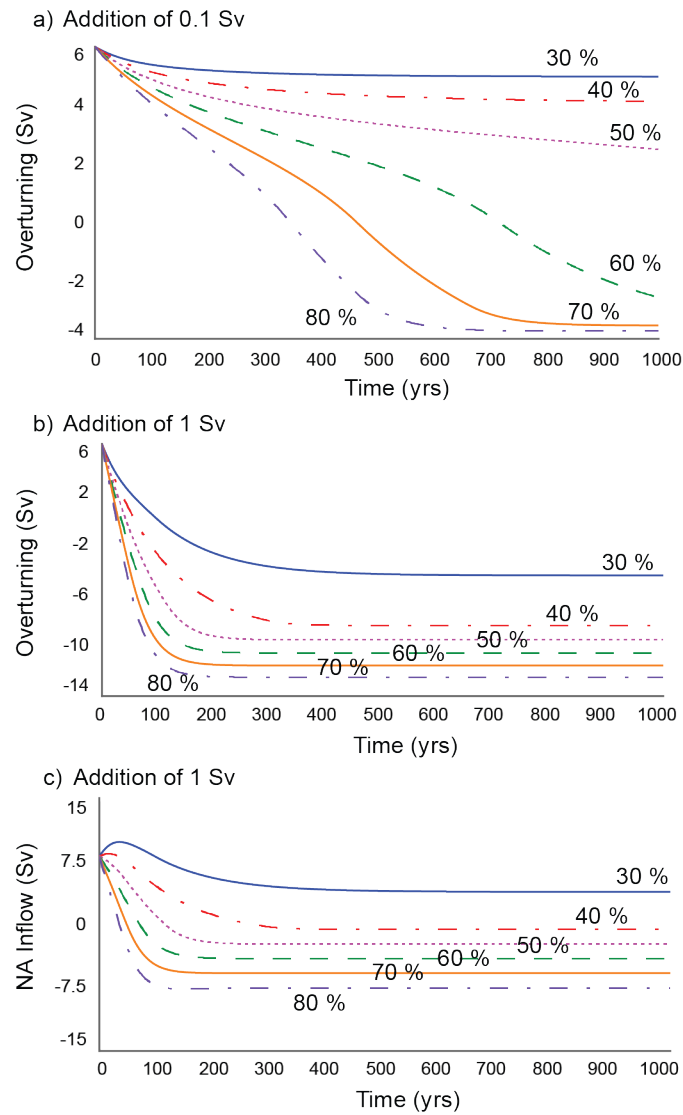
5 **Figure 1:** Schematic of the three regimes of the double estuarine circulation: thermal ( $\Psi_o > 0, \Psi_I > 0$ ), haline ( $\Psi_o < 0, \Psi_I < 0$ ) and throughflow ( $\Psi_o < 0, \Psi_I > 0$ ). The position of the arrows on the map represents the sign of a given flux and not its actual geographic location.

Freshwater forcing applied in the Nordic Seas

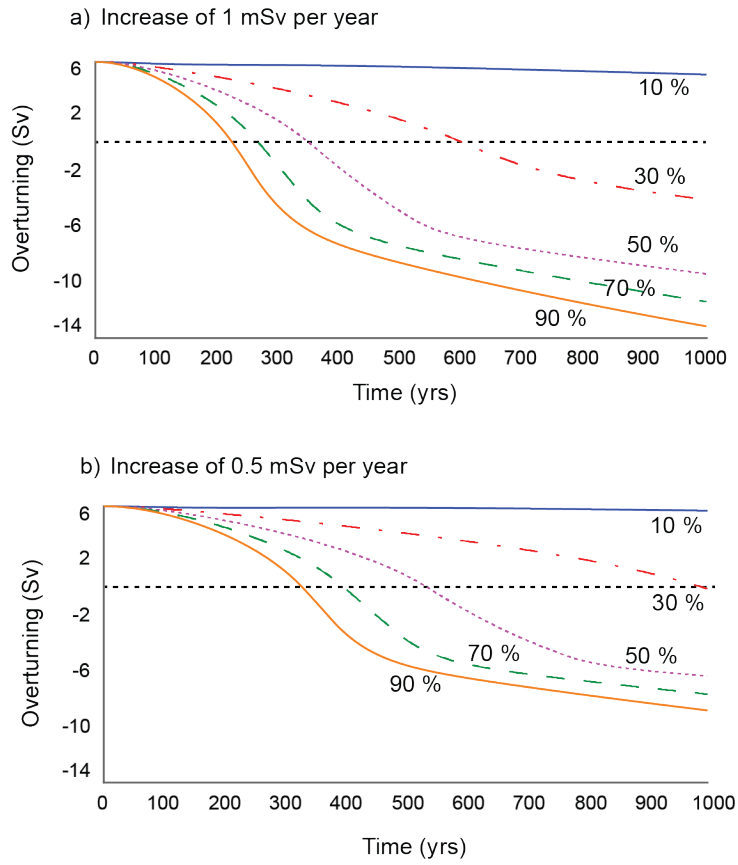
Freshwater forcing applied in the Nordic Seas and the Arctic halocline



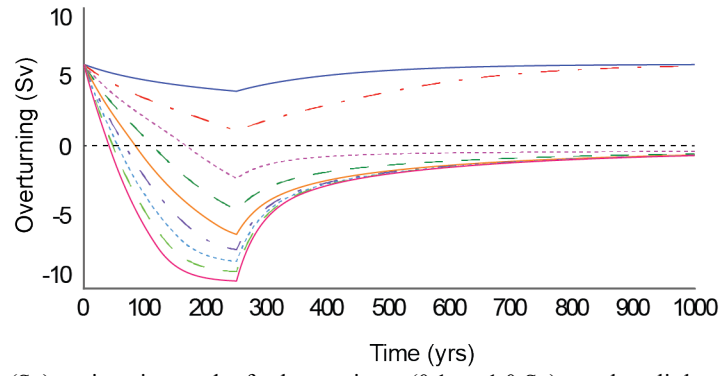
**Figure 2:** **a)** Overturning (Sv) in function of time (per 20 years of simulation) for various amount of freshwater injected in the Nordic Seas (in mSv). The black dashed line represents the steady-state of the model, with 0 mSv of freshwater injected. The overturning reaches zero for value > 29 mSv. Lines representing experiment for freshwater injection of 34 (dashed blue), 35 (dashed green), 36 (solid pink) and 37 mSv (dashed light blue) where not labelled to improve clarity of the figure. **b)** Overturning (Sv) in function of time (per year of simulation) for larger amount of freshwater injected in the Nordic Seas (in Sv). Lines representing experiment for freshwater injection of 0.4 (dashed dark green), 0.5 (solid orange), 0.6 (dashed purple), 0.7 (dashed blue), 0.8 (dashed green), and 0.9 Sv (solid pink) where not labelled to improve clarity of the figure. **c)** Overturning (Sv) in function of time (per 20 years of simulation) for various amount of freshwater injected in the Nordic Seas and the Arctic halocline (in mSv). The amount represents the total amount of freshwater injected, for which 50% was directed in the Nordic Seas and 50% in the Arctic halocline. The black dashed line represents the steady-state of the model, with 0 mSv of freshwater injected. The overturning reaches zero for value > 86 mSv. Lines representing experiment for freshwater injection of 91 (dashed blue), 92 (dashed green), 93 (solid pink) and 94 mSv (dashed light blue) where not labelled to improve clarity of the figure. **d)** Overturning (Sv) in function of time (per year of simulation) for larger amount of freshwater injected in the Nordic Seas and the Arctic halocline (in Sv). The amount represents the total amount of freshwater injected, for which 50% was directed in the Nordic Seas and 50% in the Arctic halocline. Lines representing experiment for freshwater injection of 0.4 (dashed dark green), 0.5 (solid orange), 0.6 (dashed purple), 0.7 (dashed blue), 0.8 (dashed green), and 0.9 Sv (solid pink) where not labelled to improve clarity of the figure.



5 **Figure 3:** Overturning strength (Sv) against time under constant Nordic Seas and Arctic halocline freshwater input of **a)** 0.1 and **b)** 1.0 Sv. Also, we represented the **c)** North Atlantic inflow against time under the same condition as **b)**. The percentages represent the proportion of freshwater released in the Nordic Seas, the remaining being discharge in the Arctic halocline.



5 **Figure 4:** Overturning strength (Sv) against time under increasing Nordic Seas and Arctic halocline freshwater input of **a)** 0.01 and **b)** 0.005 Sv per year of simulation. The percentages represent the proportion of freshwater released in the Nordic Seas, the remaining being discharged in the Arctic halocline. The dashed black line represents overturning = 0.



5 **Figure 5:** Overturning strength (Sv) against time under freshwater input (0.1, to 1.0 Sv) evenly split between the Nordic Seas and Arctic halocline. The freshwater was released during the first 249 years of the experiment, then the circulation was allowed to recover from the year 250 onward.

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