

Climate-state dependence of multi-centennial variability in the Atlantic Meridional Overturning Circulation

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ABSTRACT

Multi-centennial variability of the Atlantic Meridional Overturning Circulation (AMOC) is a fundamental feature of the Earth system, influencing climate variability across past and future warmer climate states. Yet it remains unclear how such low-frequency, internally generated variability responds to changes in the background climate state under greenhouse-gas forcing. Here we investigate the sensitivity of multi-centennial AMOC variability using multi-millennial equilibrium simulations with the EC-Earth3 climate model under three CO₂ concentrations (280, 400 and 560 ppm). All simulations exhibit pronounced low-frequency variability in global mean surface air temperature, with the strongest amplitudes in the subpolar North Atlantic and Arctic, closely linked to AMOC fluctuations. Spectral analyses reveal a dominant self-sustained AMOC mode with a period of approximately 200 – 300 years, primarily maintained by

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subtropical-subpolar salinity-advection feedback, which persists across all climate states examined. In addition, a secondary mode with a period of 100 – 150 years is identified, associated with Arctic sea-ice-freshwater interactions. This Arctic-related mode weakens substantially under elevated CO₂ forcing as Arctic sea ice retreats. These results demonstrate that multi-centennial AMOC variability arises from both climate-state-independent and climate-state-dependent mechanisms. While the mean AMOC weakens under greenhouse-gas forcing, internal low-frequency variability remains an active component of the climate system, with important implications for interpreting long-term climate variability in both past and future warm climates.

Key words: multi-centennial variability; AMOC; EC-Earth; climate sensitivity

Article Highlights:

- In EC-Earth3 equilibrium simulations, primary AMOC mode driven by subtropical–subpolar salinity-advection feedback persists across 280–560 ppm CO₂ states.
- Secondary AMOC mode linked to Arctic sea-ice–freshwater interactions weakens substantially as Arctic sea ice retreats under warmer climate states.
- Multi-centennial AMOC variability combines a robust, climate-state-independent mode with a climate-state-dependent mode.

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1. Introduction

Understanding low-frequency climate variability during the Holocene is essential for elucidating the processes that shaped past environmental change and human societies, and for understanding how internal climate variability operates across different background climate states. Paleoclimate proxy records consistently reveal pronounced multi-centennial variability, particularly in the North Atlantic region (Delworth and Mann, 2000; Sicre et al., 2008; Mann et al., 2009; Askjær et al. 2022). Askjær et al. (2022) demonstrated this variability through an integrated analysis of proxy reconstructions and transient climate simulations, identifying dominant spectral power in the 100–250 year band. The strongest amplitudes are typically observed in the subpolar North Atlantic and Arctic, suggesting that key oceanic feedbacks – such as salinity transport and sea-ice interactions – play a central role. Despite relatively weak external forcing during the Holocene, these low-frequency fluctuations appear to exert a disproportionate influence on regional and hemispheric climate variability.

Climate variability on multi-decadal to multi-centennial timescales arises from a combination of internal climate dynamics (Bakker et al., 2017; Zhang et al., 2019; Mann et al., 2014) and external forcings, including solar variability, volcanic eruptions, and greenhouse-gas changes (Otterå et al., 2010; Mann et al., 2021; Sun et al., 2022). Modeling studies suggest that external forcings explain only a limited fraction (approximately 10–35%) of the climate variance on these timescales during the past two millennia (Moffa-Sánchez et al., 2019), implying a substantial contribution from internal

processes. Consistent with this view, long control simulations with coupled climate models – including HadCM3 (Vellinga and Wu, 2004), CESM (Yang et al., 2024), and EC-Earth3 (Meccia et al., 2022; Cao et al., 2023) – exhibit pronounced multi-centennial variability even in the absence of time-varying external forcing. However, the dominant physical mechanisms responsible for this variability, and their sensitivity to the background climate state, remain debated.

A growing body of work points to the Atlantic Meridional Overturning Circulation (AMOC) as a key driver of low-frequency climate variability (Msadek and Frankignoul, 2009; Menary et al., 2012). Multi-centennial temperature fluctuations have been linked to AMOC variations driven by salinity anomalies in the subpolar North Atlantic (Delworth and Zeng, 2012; Li and Yang, 2022). Through its role in northward heat transport, the AMOC strongly influences Arctic and North Atlantic climates and modulates atmospheric circulation patterns, including shifts in the Intertropical Convergence Zone (Liu et al., 2022; Bellomo and Mehling, 2024). While proxy reconstructions and model simulations indicate that the mean strength of the AMOC remained relatively stable throughout the Holocene (Jiang et al., 2023), its internal multi-centennial variability, and its response to different equilibrium climate states remains poorly constrained (Cini et al., 2025; Ferster et al., 2025).

The physical origin of AMOC multi-centennial variability has been explored primarily using long control simulations, owing to limited instrumental records and uncertainties in past external forcings. Across a range of coupled models, multi-centennial AMOC oscillations have been reported, but their driving mechanisms differ. Some studies emphasize the role of Southern Ocean processes (Delworth and Zeng, 2012;

Martin et al., 2013, 2015), whereas others highlight freshwater and salinity exchanges between the Arctic and the North Atlantic (Yang et al., 2024; Li and Yang, 2022; Jiang et al., 2021). Recent work with EC-Earth3 has identified a self-sustained AMOC mode associated with salinity advection feedback in the North Atlantic, suggesting the presence of intrinsic oscillatory mode in the coupled ocean system (Cao et al., 2023; Ferster et al., 2025). He et al. (2026), using multi-model piControl simulations, demonstrated that multi-centennial AMOC variability exerts a detectable influence on the Afro-Asian summer monsoon, providing independent evidence that such internal variability is not merely a model artifact but reflects a robust feature of the climate system.

From a theoretical perspective, low-frequency climate variability is often interpreted as the red noise response of the ocean to stochastic atmospheric forcing (Hasselmann, 1976), with stabilizing negative feedback limiting long-term variability. However, idealized and intermediate-complexity models have long demonstrated the possibility of self-sustained oscillations arising from nonlinear ocean dynamics, including salinity-advection feedback and density-driven circulation changes (Welanders, 1982; Rind and Tziperman, 1997; Zhang et al., 2002; Colin de Verdière et al., 2006). Recent box-model studies have further shown that sub-polar salinity anomalies alone can generate multi-centennial AMOC oscillations with periods set by upper-ocean adjustment timescales (Li and Yang, 2022). Yet the extent to which such mechanisms operate in comprehensive climate models, and how they respond to changes in background climate state, remains unclear.

In a warming climate, enhanced stratification and surface freshening are expected to weaken the mean AMOC (Rahmstorf et al., 2015; Brodeau and Koenigk, 2016; Caesar et al., 2018), potentially altering its internal variability. Previous studies suggest that AMOC oscillations may weaken under warmer conditions due to climate-state-dependent feedbacks, including reduced Arctic sea-ice and modified freshwater transport (Yang et al., 2024). However, many existing simulations are too short to fully capture deep-ocean adjustment and low-frequency variability (van der Linden et al., 2019). Recent work indicates that the amplitude and persistence of AMOC variability depend on the background climate state, with warmer and saltier conditions potentially enhancing certain oscillatory modes (Cini et al., 2025; Ferster et al., 2025).

Here, we use multi-millennial equilibrium simulations with the EC-Earth3 climate model to examine how internal AMOC multi-centennial variability depends on the background climate state, as sampled here by different greenhouse-gas concentration levels. By comparing simulations under pre-industrial, present-day, and doubled-CO₂ conditions, we assess how internal AMOC modes persist or change across climate states and identify the mechanisms governing their variability. This approach allows us to isolate robust internal processes from climate-state-dependent feedbacks, providing new insight into the origin of low-frequency AMOC variability and its relevance for past and future climate change.

2. Methods

2.1 Model description

EC-Earth is a fully coupled Earth system model that integrates atmospheric, oceanic, sea ice, land, and biospheric components and is widely used in climate change simulations, predictions, and sensitivity studies (Hazeleger et al., 2010, 2012; Bellomo and Mehling, 2024). In this study, we use the EC-Earth3 configuration optimized for long equilibrium simulations. The EC-Earth3 couples the Integrated Forecasting System (IFS) atmosphere to the NEMO ocean model, the LIM3 sea-ice model, and the HTESSEL land surface scheme.

The atmospheric component (IFS cycle 36r4) operates at a TL159 horizontal resolution (320×160 longitude/latitude, ~ 125 km) with 62 vertical levels up to 5 hPa. The land surface is represented by HTESSEL at the same horizontal resolution. The ocean component, NEMO3.6, uses an ORCA1 tripolar grid with nominal 1° horizontal resolution, refined to $1/3^\circ$ in the tropics (362×292 longitude/latitude), and 75 vertical levels. Sea ice is simulated using the dynamic-thermodynamic LIM3 model with five ice thickness categories, which is suitable for studies of long-term AMOC variability. As in most comprehensive climate models, interactive Greenland and Antarctic ice sheet dynamics are not included.

A comprehensive description and evaluation of EC-Earth3 is provided in Döscher et al. (2022). Deep convection in the Labrador and Irminger Seas is active in the piControl simulation, with mixed layer depths exceeding 1000 m in winter, within the typical range of CMIP6 models. The mean AMOC strength at 26°N in the EC-Earth3 piControl simulation is approximately 17.5 Sv (Meccia et al., 2022), same as in our pre-industrial simulation, which is broadly consistent with the observational estimate of 17.2 Sv from the RAPID array at 26.5°N . Some biases exist—notably in the seasonal cycle of mixed

layer depth and in the representation of Arctic freshwater outflow—which are documented in Döscher et al. (2022) and are common across CMIP6 models.

2.2 Experiment design

Three equilibrium experiments were conducted with prescribed atmospheric CO₂ concentrations of 280 ppm (E280), 400 ppm (E400), and 560 ppm (E560), representing pre-industrial, present-day, and doubled-CO₂ climate states, respectively (Table 1). All simulations were initialized from the same pre-industrial control state.

Table 1. Summary of the different model experiments considered in this study.

Experiments	CO ₂ [ppmv]	Simulation length / Duration in this study	T _{global} [°C]	AMOC (Sv)
E280	280	1990-3995 / 1996-3995	14.6	17.5
E400	400	1990-5058 / 3059-5058	16.8	17.0
E560	560	1990-5002 / 3003-5002	18.6	15.7

The E280 simulation was integrated for approximately 2000 years. The E400 and E560 simulations were integrated for more than 3000 years to ensure adjustment of the deep-ocean and the AMOC. Although the atmosphere responds rapidly to changes in radiative forcing, the large heat capacity of the ocean and long ventilation timescales associated with the AMOC require multi-centennial to millennial integrations to reach quasi-equilibrium.

To analyze internal multi-centennial variability under equilibrium conditions, we use the final 2000 years of each simulation. Over this period, linear trends in global mean surface air temperature are less than 0.02°C per century, and trends in upper, intermediate, and deep-ocean temperatures are all below 0.05°C per century (Table S1 in

Supplementary material), indicating that the coupled system has reached quasi-equilibrium (Li et al., 2013).

2.3 Data processing and analysis

All model output was linearly detrended prior to analysis to remove residual long-term drift. Ocean variables were regridded to a 320×160 longitude – latitude grid to match the atmospheric resolution. Time series were analyzed using standard spectral techniques, including multitaper and Fourier power spectral analyses, with significance assessed relative to a red-noise background.

Low-frequency variability was isolated using a Lanczos low-pass filter with a cutoff period of 100 years and 201 filter weights. Regression and correlation analyses were performed on the filtered time series, and statistical significance was evaluated using a two-sided Student's t-test with effective degrees of freedom estimated from the filtered data.

The maximum AMOC index is defined as the annual mean maximum of the meridional overturning streamfunction between 200 and 3000 m depth and $20^\circ \text{ N} - 70^\circ \text{ N}$. The Greenland – Scotland Ridge overturning circulation (GSOC) index is defined as the maximum meridional streamfunction across the Greenland – Scotland Ridge. The North Atlantic Deep-Water Formation (NADWF) region is defined to include the Labrador Sea, Irminger Sea, and Greenland – Iceland – Norwegian Seas, excluding the Hudson Bay and Baltic Sea.

Salt and freshwater budgets for the NADWF region were computed by integrating advective, surface, and vertical fluxes across the region's boundaries, following standard formulations.

3. Results

3.1 Multi-centennial climate variability in different climate states

We first examine the characteristics of low-frequency climate variability under different greenhouse-gas forcing levels. The 2000-year mean global mean surface air temperature (GMSAT) increases from $14.6 \pm 0.2^\circ\text{C}$ in the pre-industrial simulation (E280) to $16.8 \pm 0.1^\circ\text{C}$ in E400 and $18.6 \pm 0.1^\circ\text{C}$ in E560 (Fig 1a-c).

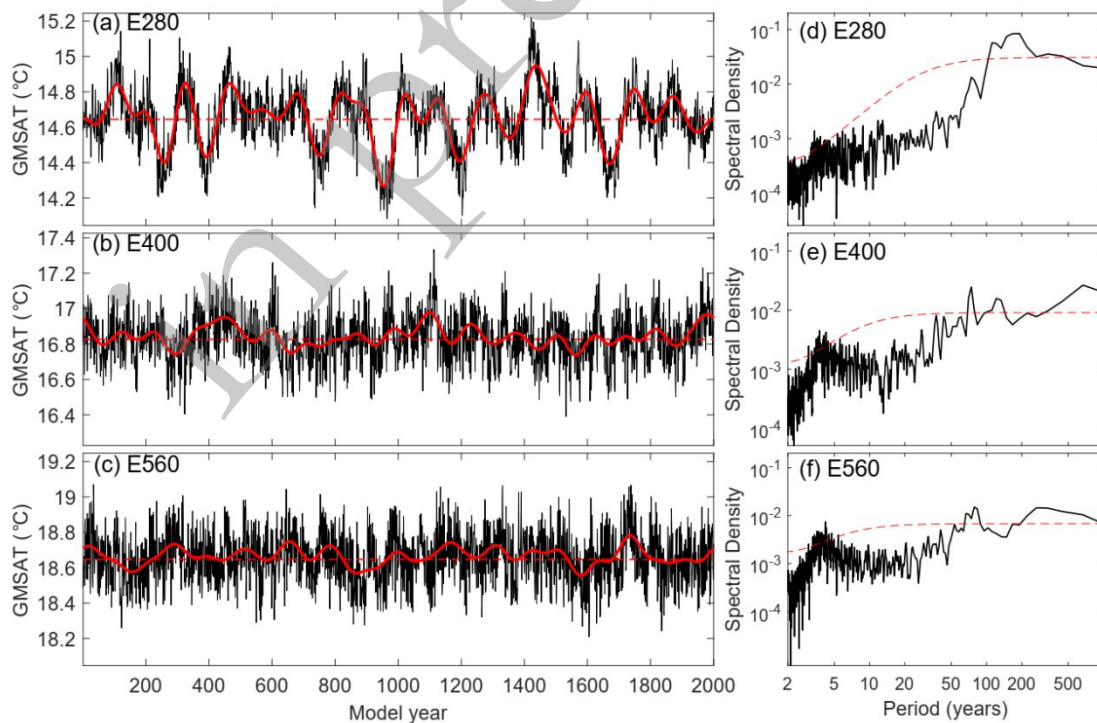


Fig. 1. Global mean surface air temperature (GMSAT) time series and the power spectrum for the three experiments. GMSAT time series for the simulations: (a) E280,

(b) E400, and (c) E560. The bold red curves indicate the low-pass filtered series (using the Lanczos method with 201 weights and a cutoff period of 100 years); (d – f) Power spectrum analysis of the GMSAT time series, where the dashed curves indicate 95% red noise.

All simulations exhibit pronounced low-frequency variability in GMSAT, with visibly reduced amplitudes under warmer climate conditions. Power spectral analysis reveals dominant multi-centennial peaks at ~190 years in E280, at 121 and 667 years in E400 (with the 667-year peak being much broader), and at 267 years in E560 (Fig. 1d-f), superimposed on a red-noise background. These results indicate that multi-centennial variability persists across climate states, although its amplitude and dominant timescales are modulated across climate states under greenhouse-gas forcing.

To assess the regional origin of this variability, we analyzed surface air temperature (SAT) variability in the Northern Hemisphere extratropics, tropics, and Southern Hemisphere extratropics (Fig. S1 in Supplementary material). Multi-centennial variability is strongest in the Northern Hemisphere extratropics, whereas tropical SAT variability is largely confined to interannual timescales under elevated CO₂ forcing. The Southern Hemisphere extratropics exhibit weaker and longer-timescale variability. These results indicate that GMSAT multi-centennial variability is primarily driven by Northern Hemisphere processes.

Spatial correlations between annual mean SAT and the low-pass-filtered GMSAT (100-year cutoff) further show that multi-centennial variability is concentrated in the subpolar North Atlantic and Arctic under pre-industrial conditions (Fig. S2 in Supplementary Material). This pattern points to ocean circulation processes as a key

driver of low-frequency climate variability. We therefore focus on the Atlantic Meridional Overturning Circulation (AMOC) to investigate the oceanic origin of the simulated multi-centennial climate fluctuations.

3.2 AMOC variability across different climate states

Under pre-industrial conditions (E280), multi-centennial climate variability is most pronounced in the North Atlantic and Arctic, consistent with AMOC-driven fluctuations in oceanic heat transport associated with deep-water formation and buoyancy forcing (Delworth and Zeng, 2012; Li and Yang, 2022; Zhang, 2010; Yeager and Danabasoglu, 2014). To assess the sensitivity of this variability to greenhouse-gas forcing, we analyze AMOC variations across the three climate states using the maximum AMOC index, defined as the annual mean maximum overturning stream function between 200 and 3000 m depth and 20° N – 70° N.

The mean AMOC strength decreases with increasing CO₂ forcing, from 17.5 ± 1.3 Sv in E280 to 17.0 ± 0.9 Sv in E400 and 15.7 ± 0.9 Sv in E560 (Fig.2a-c), indicating a systematic weakening in warmer climates. Despite this weakening, all simulations exhibit pronounced multi-centennial AMOC variability. Power spectral analysis reveals dominant peaks at approximately 191 years in E280, 148 years in E400, and 267 years in E560 (Fig. 2d-f), closely matching the multi-centennial timescales identified in GMSAT.

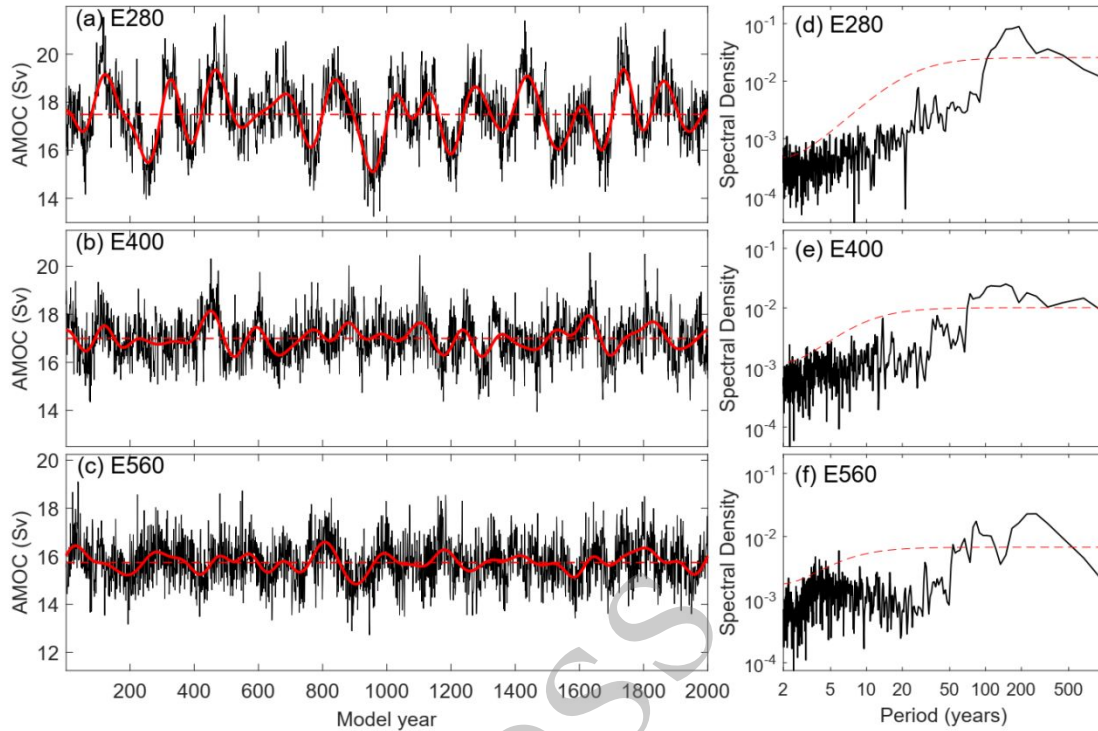


Fig. 2. Maximum Atlantic Meridional Overturning Circulation (AMOC) time series and power spectrum for the three experiments. Maximum AMOC time series for the (a) E280, (b) E400, and (c) E560 simulations, where the bold red curves indicate the low-pass filtered series (using the Lanczos method with 201 weights and a cutoff period of 100 years); (d–f) Power spectrum analysis of the maximum AMOC time series, where the dashed curves indicate 95% red noise.

Low-pass-filtered AMOC and GMSAT time series are strongly correlated, with correlation coefficients of 0.89 in E280, 0.49 in E400 and 0.55 in E560, all significant at 95% confidence level. These results demonstrate that AMOC variability remains a primary driver of multi-centennial temperature fluctuations across climate states, although its coupling to surface temperature weakens under elevated greenhouse-gas forcing.

The mean meridional overturning stream function further illustrates systematic changes in AMOC structure with warming (Fig. 3). Increasing CO₂ leads to a weaker and shallower overturning cell south of approximately 65° N, while northward transport intensifies at higher latitudes (see vertical profile in Fig. S3 in Supplementary material). This pattern reflects enhanced "Atlantification" of the Arctic Ocean under warmer conditions and is consistent with proxy evidence for increased Atlantic inflow during past warm periods (Vermassen et al., 2023). The contrasting response south and north of 65° N indicates a redistribution of overturning strength rather than a uniform weakening.

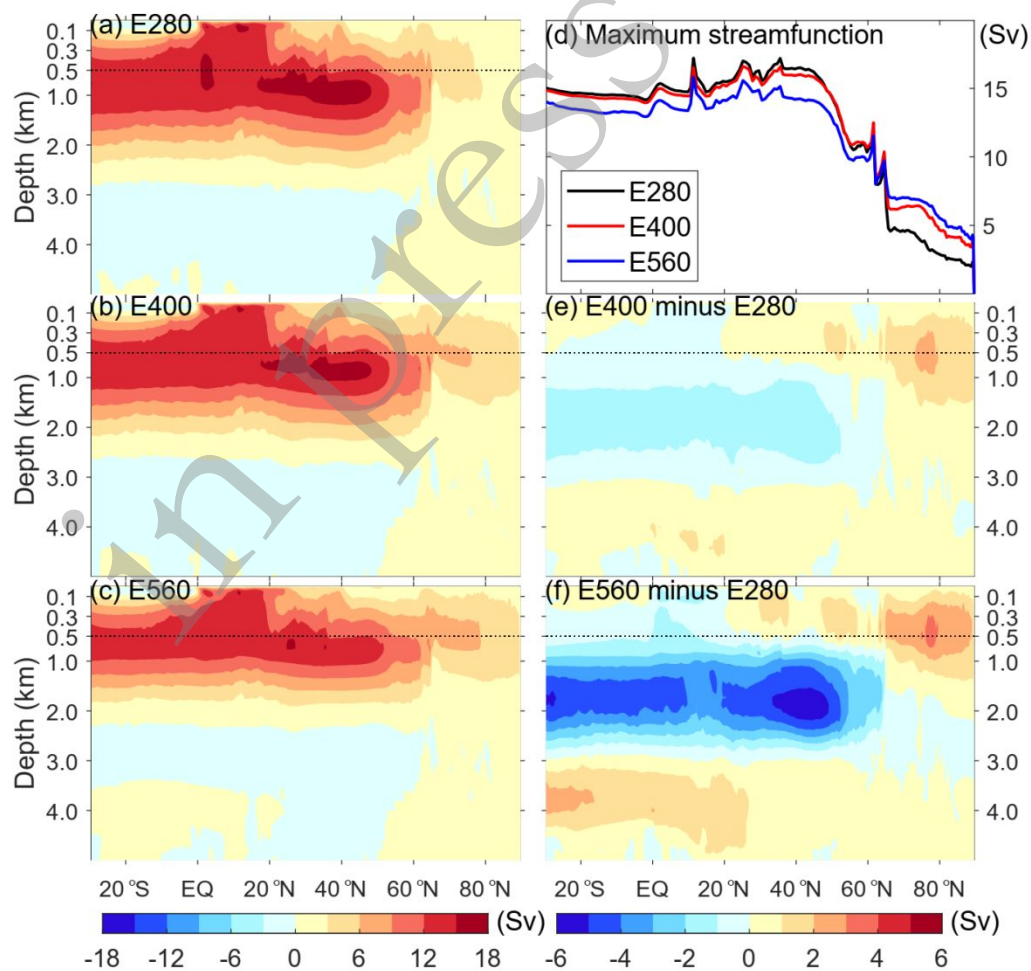


Fig. 3. Meridional streamfunction in the North Atlantic Ocean. The mean meridional streamfunction for the three simulations: (a) E280, (b) E400, and (c) E560; (d) The maximum meridional streamfunction computed at each latitude across the three simulations; (e~f) Changes in the meridional streamfunction in the E400 and E560 simulations with respect to the E280 simulation.

To further quantify high-latitude overturning changes, we introduce the Greenland-Scotland Ridge overturning circulation (GSOC) index, defined as the maximum meridional stream function across the Greenland-Scotland Ridge (Friedrich et al., 2010). Under pre-industrial conditions, the GSOC closely tracks AMOC variability at multi-centennial timescales (Fig. 4a,d), indicating a tight coupling between subpolar overturning and basin-scale AMOC variability. In warmer climates, however, the low-frequency variability of the GSOC is substantially reduced (Fig. 4b,c,e,f), coincident with extensive Arctic sea-ice retreat. This decoupling suggests that Arctic processes contribute to multi-centennial AMOC variability primarily under colder climate conditions.

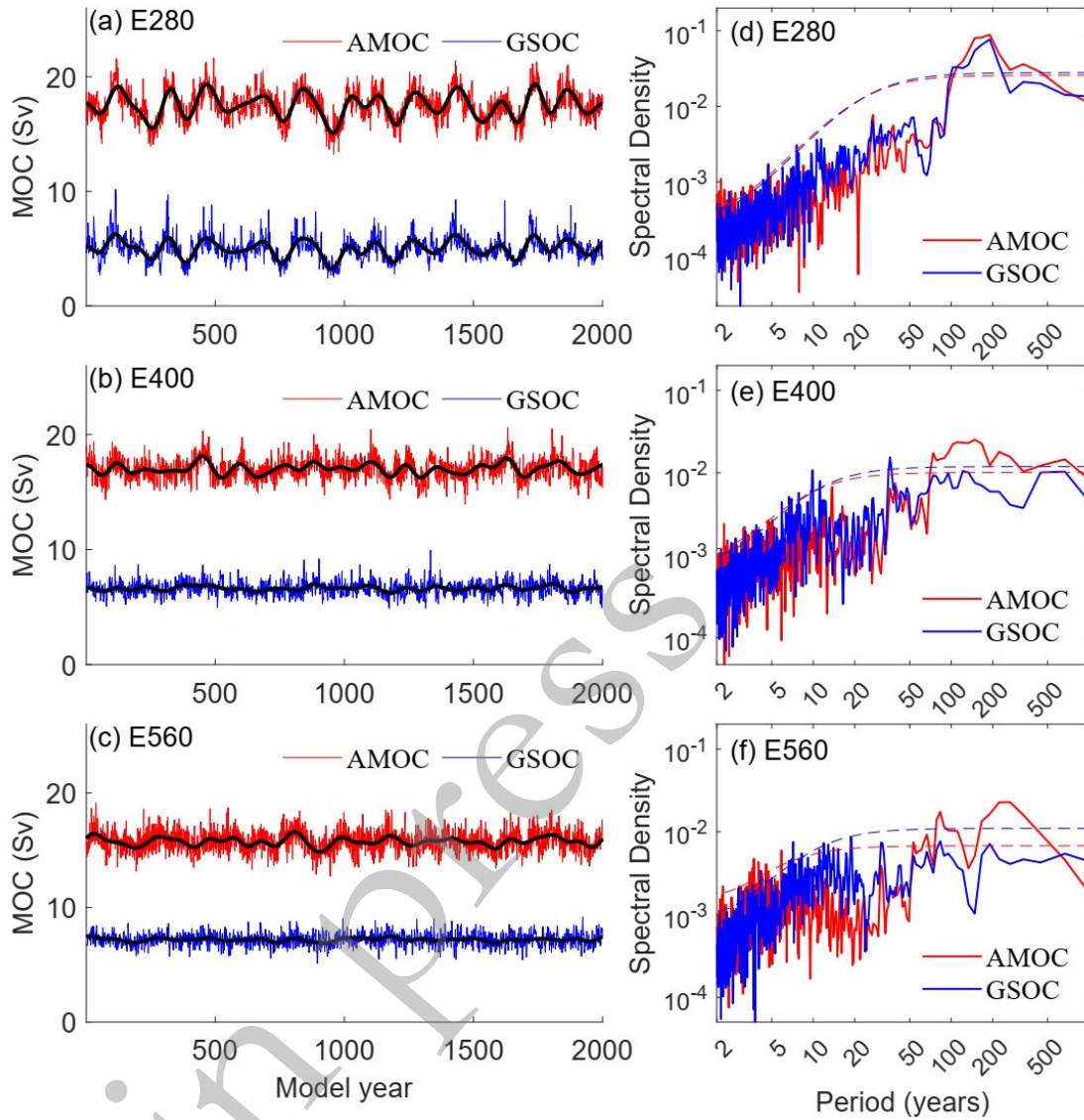


Fig. 4. Variations of Atlantic Meridional Overturning Circulation (AMOC) index and Greenland-Scotland Ridge overturning circulation (GSOC) index. (a~c) Comparison of the low-pass filtered AMOC index and the GSOC index revealed in our three CO₂ forcing simulations: (a) E280, (b) E400, and (c) E560; and (d~f) their power spectra.

3.3 Mechanisms underlying multi-centennial variability

The persistence of multi-centennial AMOC variability across all experiments raises the question of the physical mechanisms sustaining these oscillations under different climate states. Previous studies have highlighted the role of the Arctic Ocean in driving low-frequency AMOC variability through fresheater and sea-ice processes (Li and Yang, 2022; Jiang et al., 2021). During periods of a strong AMOC, enhanced northward heat transport warms the Arctic Ocean, promoting sea-ice melt and increasing freshwater export to the North Atlantic, which suppresses deep convection and subsequently weakens the AMOC - a process often referred to as the "Arctic-origin" mechanism (Yang et al., 2024; Jiang et al., 2021; Mehling et al., 2022).

To examine this mechanism, we regress ocean mixed-layer depth (MLD) onto the low-pass filtered AMOC index. Under pre-industrial conditions (E280), positive AMOC anomalies are associated with enhanced MLD in the Greenland-Iceland-Norwegian (GIN) and Labrador Seas (Fig. 5a), indicating that a stronger AMOC intensifies deep convection in these regions. Conversely, negative AMOC anomalies correspond to reduced MLD, suggesting enhanced upper-ocean stratification, consistent with the long-term stratification trends reported by Li et al. (2020). These MLD anomalies closely follow the mean Arctic Sea ice edge (Zampieri et al., 2018; Batté et al., 2020), indicating a strong coupling between sea-ice variability and deep-water formation regions.

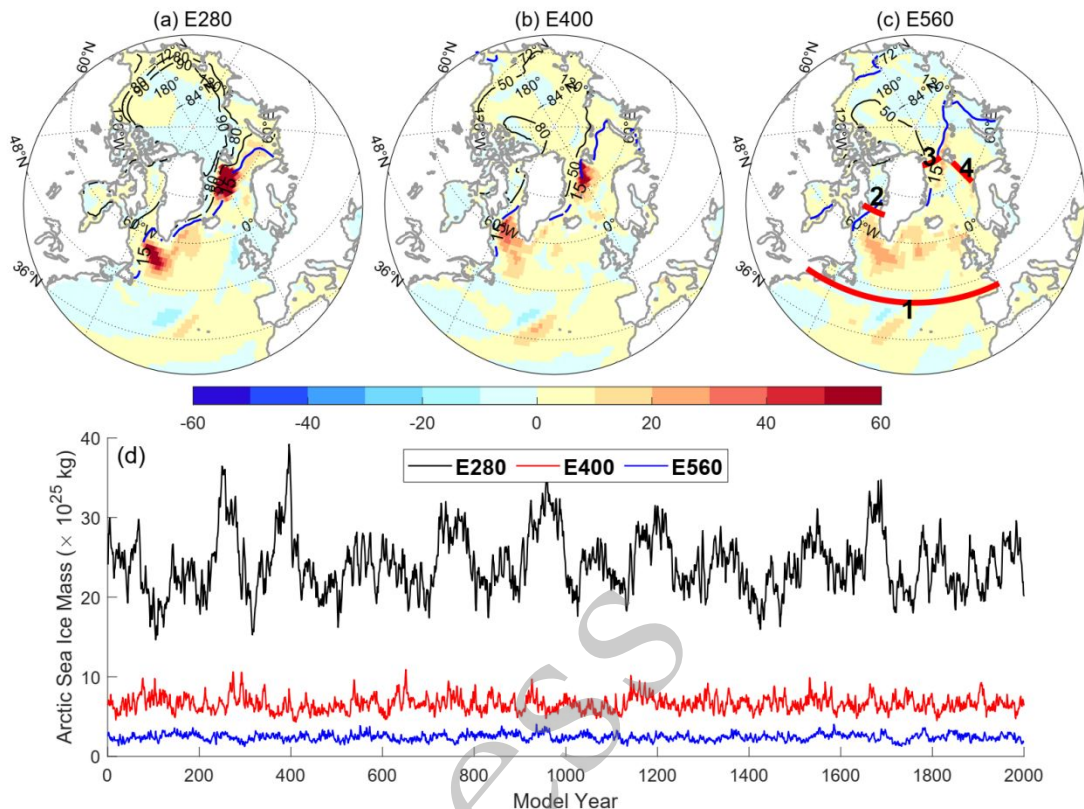


Fig. 5. Ocean mixed layer depth being regressed onto the low-pass filtered AMOC index and the total mass of sea-ice within pole region. (a~c) Ocean mixed layer depth being regressed onto the low-pass filtered AMOC index (shaded, unit: m), and 2000-year mean sea-ice concentration (contour, only 15%, 50%, and 80% are shown, in which the 15% is considered as the sea-ice edge shown as blue curve); (d) The total mass of sea-ice within pole region north of 66.3°N. Red lines in (c) indicate the boundaries between the North Atlantic and the Arctic through the Baffin Bay (2), the Fram Strait (3) and the Barents Sea (4), while line 1 indicates the boundary between the Subpolar and the Subtropical North Atlantic.

With increasing greenhouse-gas forcing, the magnitude and spatial extent of these MLD anomalies are substantially reduced (Fig. 5b,c). In warmer climates, enhanced

ocean stratification due to thermal expansion and widespread Arctic sea-ice loss limits the effectiveness of sea-ice – driven freshwater perturbations. This is reflected in the pronounced decrease in total Arctic sea-ice mass, from $24.17 \pm 3.71 \times 10^{25}$ kg in E280 to $6.61 \pm 0.97 \times 10^{25}$ kg in E400 and $2.43 \pm 0.44 \times 10^{25}$ kg in E560. Correspondingly, the correlation between Arctic sea-ice mass and AMOC strength weakens from -0.61 in E280 to -0.25 in E400 and E560 (Fig. 5d), remaining statistically significant only under pre-industrial conditions.

These results indicate that Arctic sea-ice – freshwater interactions contribute to multi-centennial AMOC variability primarily under colder climate states. As greenhouse-gas forcing increases and Arctic sea ice retreats, this mechanism becomes progressively less effective. The continued presence of pronounced multi-centennial AMOC variability in warmer climates therefore implies the operation of additional mechanisms that do not rely on Arctic sea ice, motivating an examination of salinity-driven processes within the North Atlantic.

3.3.1 The key role of North Atlantic Deep-Water Formation (NADWF) Region

Low-frequency AMOC variability is fundamentally linked to density variations in regions of North Atlantic deep-water formation (Danabasoglu et al., 2008; Delworth and Zeng, 2012; Dima et al., 2022; Zhao et al., 2024). To isolate the processes governing these density changes, we focus on the North Atlantic Deep-Water Formation (NADWF) region following Delworth and Zeng (2012), encompassing the Labrador Sea, Irminger Sea, and Greenland-Iceland-Norwegian (GIN) Seas, while excluding Hudson Bay and the Baltic Sea. This region connects to the subtropical North Atlantic at 45° N, to the Arctic

through the Baffin Bay, Fram Strait, and Barents Sea, and to the deep ocean below 1000 m.

We analyze the upper 1000 m of the NADWF region, which contains approximately $\sim 7.37 \times 10^{15} \text{ m}^3$ of seawater and directly influences overturning strength. Mean-state properties show a progressive decrease in potential density and salinity, and an increase in temperature, under elevated CO_2 forcing (Table 2). Despite these mean changes, the time series of NADWF-averaged density, salinity, and temperature all exhibit pronounced multi-centennial variability across the three experiments.

Table 2. This is a sample table caption and table layout. Enter as many tables as necessary at the end of your manuscript.

Experiments	Potential density [kg m^{-3}]	Salinity [Psu]	Potential temperature [$^{\circ}\text{C}$]
E280	1027.27 ± 0.03	35.06 ± 0.05	6.93 ± 0.17
E400	1026.99 ± 0.03	35.03 ± 0.03	8.72 ± 0.12
E560	1026.75 ± 0.03	35.01 ± 0.03	10.12 ± 0.13

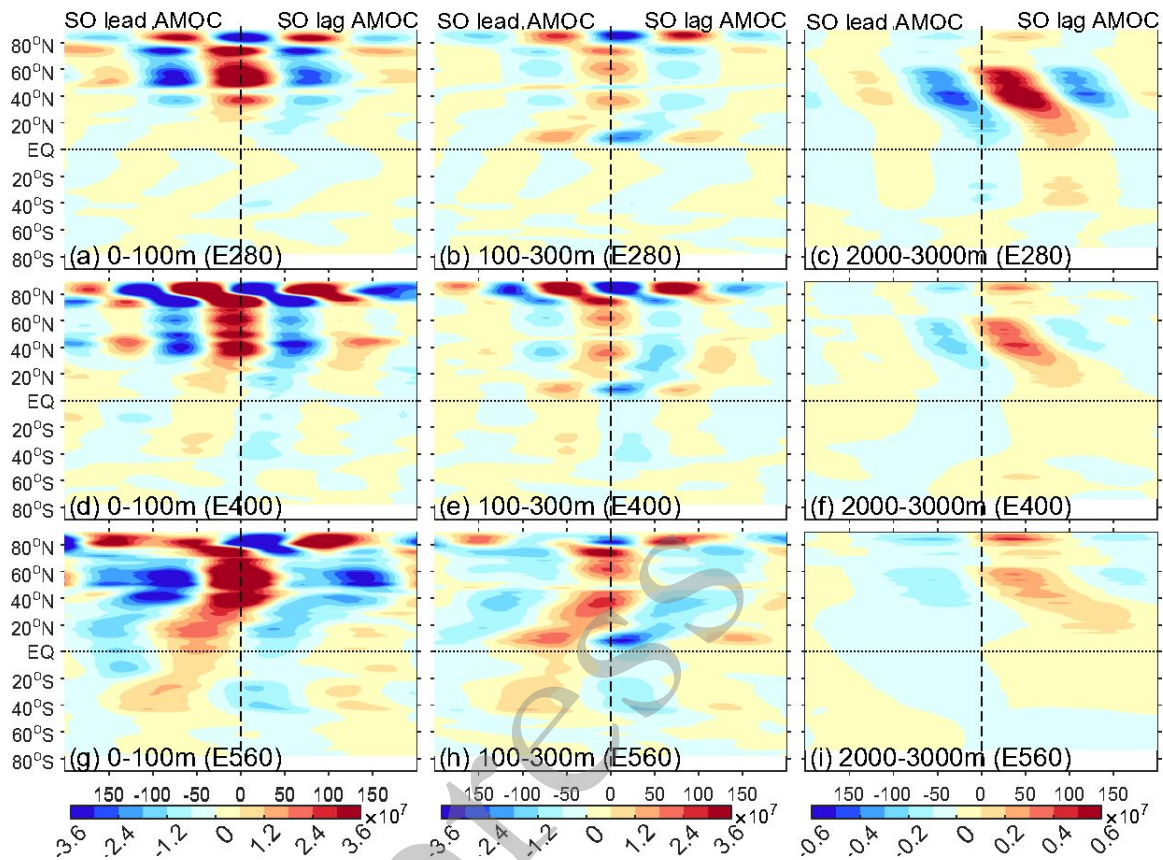
Power spectral analysis of NADWF density reveals peaks consistent with those of the AMOC index, with dominant periods of approximately 150-200 year in E280, 100-110 years in E400, and 220-270 years in E560 (Fig. S4 in Supplementary material). Linear regression of density anomalies onto the low-pass filtered AMOC index shows that stronger AMOC states are systematically associated with positive density anomalies in the deep-water formation regions, consistent with enhanced deep convection and overturning (Danabasoglu et al., 2008; Ferster et al., 2025). These results confirm that NADWF density variability provides a direct physical link between regional hydrographic changes and basin-scale AMOC fluctuations.

3.3.2 Salinity control of NADWF density variability

To identify the drivers of NADWF density variability, we examine the respective contribution of temperature and salinity. Consistent with previous studies (Delworth and Zeng, 2012; Li and Yang, 2022; Dima et al., 2022; Cao et al., 2023), salinity anomalies dominate density variations on multi-centennial timescales, whereas temperature variations act primarily as a damping influence (Fig. S5 in Supplementary material). The temperature effect on density likely stems from AMOC changes—stronger AMOC delivers more heat to the North Atlantic, causing warmer waters and decreased upper-layer density. This motivates a detailed analysis of the sources and transport pathways of salinity anomalies affecting the NADWF region.

Hovmöller diagrams in Fig. 6 presents the zonal integral of the regression coefficients of salinity across the Atlantic and Arctic basins versus the low-pass-filtered maximum AMOC time series, , reveal coherent salinity patterns across the Atlantic – Arctic system. During periods of strong AMOC, positive salinity anomalies develop in the subpolar North Atlantic (45°N–80°N) as a consequence of enhanced northward salt transport from the tropics. These positive anomalies are followed by the emergence of negative salinity anomalies in the Arctic, with the latter lagging the former by approximately 40–50 years. The salinity anomalies in the subpolar region are primarily driven by salinity variability in the upper ocean of the North Atlantic, which is dominated by meridional salinity advection between the subtropical and subpolar North Atlantic, rather than by processes related to the Arctic Ocean or South Atlantic. This interpretation is consistent with the weak amplitudes of salinity signals propagating from the South Atlantic.

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389 **Fig. 6. Salinity Regression Coefficients in the Atlantic and Arctic vs. Filtered AMOC**

390 **Index.** The zonal integral of the regression coefficients of salinity across the Atlantic and
 391 Arctic basins versus the low-pass-filtered maximum Atlantic Meridional Overturning
 392 Circulation (AMOC) time series is presented. The CO₂ forcing scenarios: (a~c) E280,
 393 (d~f) E400, and (g~i) E560, for ocean layers at depths of 0 – 100 m, 100 – 300 m, and
 394 2000 – 3000 m are given. Units are Psu m Sv^{-1} . The y-axis is the latitude and the x-axis
 395 represents lag (in years) with respect to the time of maximum AMOC. Negative (positive)
 396 values on the time axis indicate periods leading (lagging) the maximum AMOC.

397 In contrast, salinity variability at 45 ° N is strong and persistent across depths,
 398 indicating a dominant role for subtropical – subpolar salinity exchange. Arctic freshwater

signals are clearly present, particularly under pre-industrial conditions, but their contribution diminishes under elevated CO₂ forcing as Arctic sea ice retreats and freshwater export weakens. These patterns suggest that Arctic processes modulate AMOC variability but do not provide its primary sustaining mechanism.

3.3.3 Quantifying salt and freshwater fluxes into the NADWF region

To directly quantify the processes controlling NADWF salinity, we decompose salinity changes into contributions from lateral, vertical, and surface fluxes (Fig. 7). The NADWF box exchanges salt and freshwater with the subtropical North Atlantic across 45° N, with the Arctic Ocean through the Baffin Bay, Fram Strait, and Barents Sea, with the atmosphere at the surface, and with the deep ocean below 1000 m.

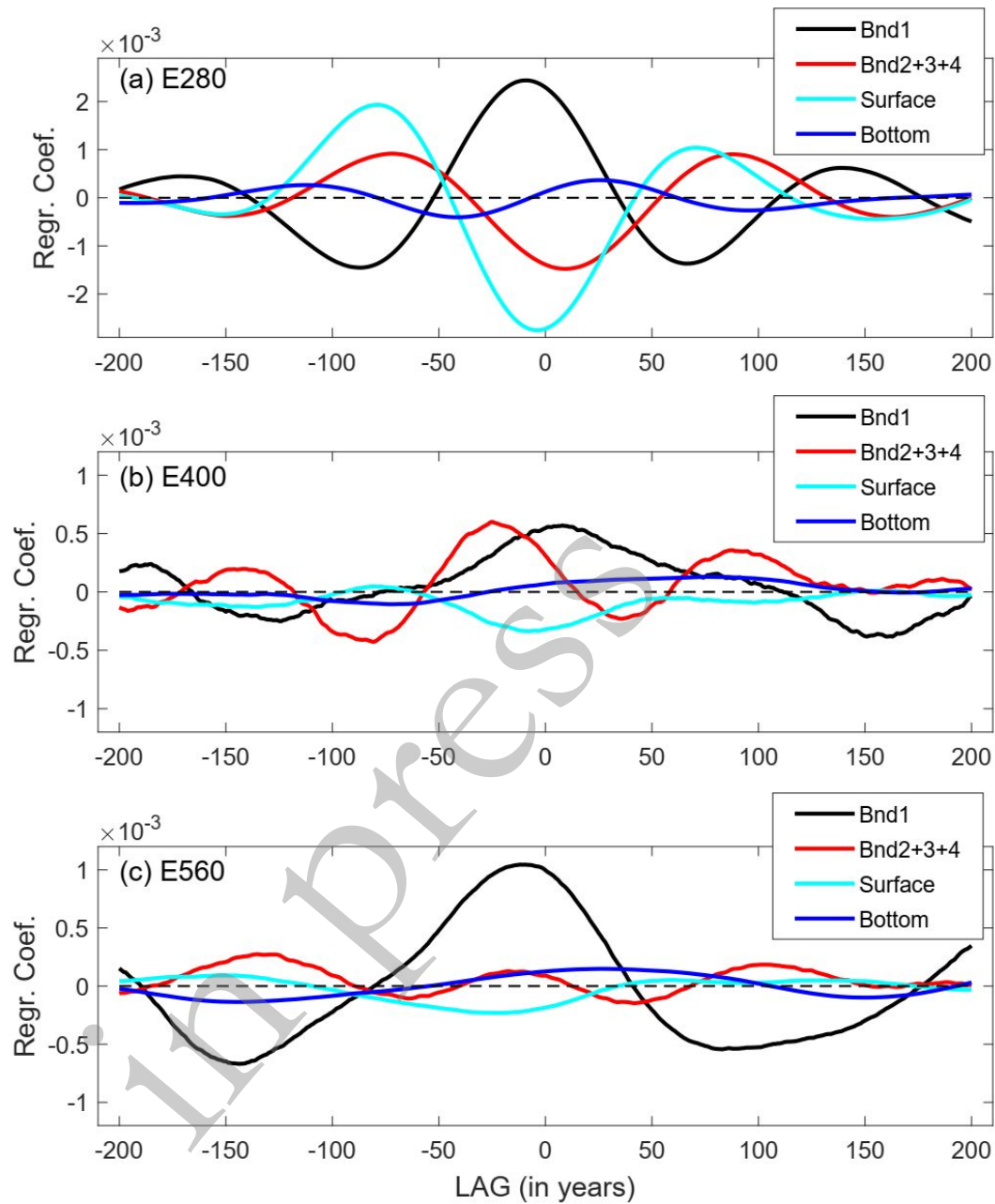


Fig. 7. Regression of salinity change in the North Atlantic Deep-Water Formation (NADWF) box induced by salt and freshwater transports. Boundaries 1 – 4 correspond to the external boundaries marked on Figure 5c, and represent transport across the 0 - 1000 m layer. The surface boundary indicates the air-sea interface, and the bottom boundary indicates the horizontal profile at 1000 m depth of the NADWF box.

Across all climate states, salt transport from the subtropical North Atlantic emerges as the dominant positive contribution to NADWF salinity variability. Regression analyses show that perturbation flows across 45° N consistently lead NADWF salinity anomalies and exhibit pronounced multi-centennial variability, with dominant periods between 150 and 300 years (Fig. S6 a,b in Supplementary material). This confirms the presence of a self-sustained subtropical–subpolar salinity-advection feedback (Mode 1) as the primary mechanism maintaining the multi-centennial AMOC variability. The self-sustained nature of this multi-centennial AMOC variability can be understood through the theoretical framework of Li and Yang (2022) . Using a single-hemisphere 4-box model, they demonstrated that the oscillation is maintained by a balance between two opposing salinity-related feedbacks. The perturbation flow of the mean subtropical–subpolar salinity gradient serves as a positive feedback, providing the continuous energy source that sustains the AMOC anomaly. In contrast, the mean advection of salinity anomalies and vertical mixing (or convection) act as negative feedbacks, constraining the AMOC anomaly and preventing unbounded growth. Crucially, Li and Yang (2022) introduced an enhanced mixing mechanism in the subpolar ocean to balance the positive salinity advection feedback—without this mechanism, the system cannot realize a self-sustained stable oscillation. The enhanced mixing is physically grounded: when AMOC is strong, weak stratification enhances mixing; when AMOC is weak, mesoscale and submesoscale eddies enhance mixing. The oscillation period is fundamentally controlled by the turnover time of the upper ocean. This theoretical framework has been validated in the EC-Earth3-LR model by Cao et al. (2023), who confirmed that the same salinity-advection–vertical-mixing interplay sustains the multi-centennial oscillation across

different climate states. This feedback operates largely independently of Arctic sea-ice conditions and persists across all climate states examined (280, 400 and 560 ppm), though its amplitude declines modestly as the mean AMOC weakens under warming.

Notably, in the E400 simulation, we observe that the relative contribution of Mode 1 compared to the secondary Mode 2 (Arctic sea-ice–freshwater interactions, 100–150 yr) increases, as the latter weakens due to partial sea-ice retreat. This is reflected in regression anomalies showing a stronger Arctic-to-subpolar signal in E400 when the two modes are compared (Fig. 6d–e). However, the absolute amplitude of the propagation signal is weaker in E400 than in E280, consistent with the overall reduction in AMOC variability under warming. In the E560 simulation, Mode 2 becomes largely negligible as sea ice retreats into the central Arctic basin, leaving Mode 1 as the only detectable mode of multi-centennial AMOC variability. The contrasting behaviors of Mode 1 and Mode 2 across the three climate states demonstrate that multi-centennial AMOC variability arises from a combination of both climate-state-independent and climate-state-dependent mechanisms, as summarized in the abstract.

Arctic freshwater fluxes are the physical carrier of the secondary Mode 2 (sea-ice–freshwater interactions, 100–150 yr), which opposes salinity increases in the NADWF region through a negative feedback loop. This contribution is strongest under pre-industrial conditions (E280), when sea-ice cover is extensive, and weakens substantially in warmer climates as sea ice retreats, with Fram Strait transport dominating the Arctic freshwater exchange (Fig. S7 in Supplementary material). Surface freshwater

fluxes further damp salinity variability, particularly in E280, whereas bottom-related processes play only a minor role across all experiments.

3.3.4 Emergence of two oscillation modes

Together, these analyses reveal the presence of two distinct oscillation modes driving multi-centennial AMOC variability. A primary mode, with a period of approximately 200 – 300 years, is driven by a self-sustained salinity-advection feedback between the subtropical and subpolar North Atlantic and persists across all climate states. A secondary mode, with a shorter period of 100 – 150 years, is associated with Arctic sea ice- freshwater interactions and becomes progressively weaker under elevated greenhouse-gas forcing. Enhanced ocean stratification and reduced meridional gradients in warmer climates act to damp both modes, but only the Arctic-related mode is strongly climate-state dependent.

The mechanistic interpretation of these two modes draws on existing theoretical and modeling studies. For the primary mode, Li and Yang (2022) in theoretically and Cao et al. (2023) in simulation experiments validated this mechanism of self-sustained subtropical–subpolar salinity-advection feedback, showing that the interplay between salinity advection and vertical mixing in the subpolar North Atlantic provides the continuous internal energy source for the oscillation.

For the Arctic sea ice induced mode, Jiang et al. (2021) demonstrated, using the IPSL-CM6-LR model, that multi-centennial AMOC variability can be driven by salinity exchanges between the Atlantic and the Arctic Ocean, with delayed freshwater accumulation and release in the Arctic playing a key role. During a strong AMOC,

reduced sea-ice volume and anomalous currents reduce freshwater export from the Arctic, leading to freshwater accumulation in the central Arctic. This mechanism is consistent with our observation that Mode 2 is active in E280 (where Arctic sea ice is extensive) and weakens substantially in warmer climates (where sea ice retreats), supporting its association with Arctic sea-ice–freshwater interactions. A full mechanistic attribution of Mode 2 would require dedicated sensitivity experiments, which are beyond the scope of the current study but are planned as future work.

4. Discussion

Using multi-millennial equilibrium simulations with the EC-Earth3 climate model, we have examined how multi-centennial AMOC variability depends on the background climate state, using greenhouse-gas forcing to sample different equilibrium climate states. Despite a systematic weakening of the mean AMOC under elevated CO₂, pronounced low-frequency variability persists in all experiments, with dominant periods ranging from approximately 100 to 300 years. This variability is closely linked to temperature fluctuations in the Northern Hemisphere extratropics, confirming the AMOC as a primary driver of multi-centennial climate variability in the simulations.

Our results demonstrate that AMOC multi-centennial variability arises from the interaction of two distinct mechanisms. A primary mode, with a period of approximately 200 – 300 years, is maintained by a self-sustained salinity-advection feedback between the subtropical and subpolar North Atlantic. This mode persists across climate states and operates largely independently of Arctic sea-ice conditions. A secondary mode, with a shorter period of 100 – 150 years, is associated with Arctic sea-ice–freshwater interactions and weakens substantially as Arctic sea ice retreats under greenhouse-gas

505 forcing. This separation provides a coherent framework for reconciling differing
506 interpretations of AMOC variability in previous modeling studies. Thus our major
507 contribution is the explicit separation of the two co-existing modes within a single model
508 framework and the quantification of their contrasting climate-state dependence.

509 The persistence of the salinity-advection-driven mode across climate states
510 highlights the robustness of internal ocean dynamics as a source of low-frequency
511 variability. Even in warmer climates characterized by enhanced stratification and reduced
512 meridional density gradients, this intrinsic mode remains active, although its amplitude is
513 damped. In contrast, the Arctic-related mode is strongly climate-state dependent,
514 consistent with earlier findings that emphasize the role of sea ice and freshwater export
515 under colder conditions. Together, these results suggest that internal AMOC variability
516 cannot be interpreted as a single mechanism but instead reflects the superposition of
517 processes with differing sensitivities to background climate conditions.

518 These findings have implications for the interpretation of Holocene climate
519 variability. Paleoclimate proxy records consistently document multi-centennial
520 variability, particularly in the North Atlantic region, even during periods of relatively
521 weak external forcing. The internally generated AMOC variability identified here
522 provides a physically grounded explanation for such fluctuations, independent of time-
523 varying external drivers. In this context, the commonly reported ~200-year Suess/de
524 Vries cycle observed in radiocarbon and cosmogenic isotope records has often been
525 attributed to solar activity (Suess, 1980; Berggren et al., 2009; Knudsen et al., 2012).
526 However, the absence of a clear solar dynamo mechanism operating at this timescale,
527 together with the limited duration of direct solar observations, leaves room for alternative

interpretations (Ma and Vaquero, 2009; Ahluwalia and Ygbuhay, 2016; Richard, 2022). Our results support the possibility that internally generated AMOC variability, through its influence on ocean – atmosphere carbon exchange, may contribute to multi-centennial variability in radiocarbon records, consistent with earlier hypotheses (Askjær et al., 2022; DeVries, 2022; Taricco et al., 2015; Prange et al., 2023). This interpretation does not exclude a solar contribution but highlights the need to account for internal oceanic processes when attributing low-frequency climate signals.

Several limitations of this study should be noted. Whether the two modes identified here are active in the real climate system remains an open question. Instrumental records are too short to resolve multi-centennial variability, and paleoclimate proxies—while providing valuable indirect evidence of past AMOC changes—face fundamental limitations in temporal resolution and dating accuracy for periods of 100–300 years. The data requirements for robustly separating two distinct spectral peaks at these timescales are extremely demanding and currently unavailable. We have therefore limited our discussion to the model world, while noting that the presence of similar multi-centennial variability across multiple CMIP6 models suggests that the underlying mechanisms are physically plausible. Future work combining high-resolution paleoclimate reconstructions with model–data assimilation approaches may help to constrain the likelihood of these modes in the real world. Dedicated sensitivity experiments (e.g., with prescribed sea-ice changes or modified salinity advection) would be needed to definitively isolate and verify the two modes. Such experiments are currently underway, but their multi-millennial integration timescales place them beyond the scope of the present study. Dedicated sensitivity experiments (e.g., freshwater perturbation experiments or experiments with

prescribed sea-ice changes) would be needed to definitively isolate and quantify the feedbacks governing Mode 2. Such experiments are currently underway, but given the multi-centennial timescale of the phenomenon, they will require considerable integration time and are beyond the scope of the present paper. As well, the simulations employ a single climate model configuration and do not include interactive ice-sheet dynamics, which may influence freshwater input and long-term AMOC behavior. In addition, EC-Earth3 is known to overestimate Arctic sea-ice extent under certain conditions, which may affect the amplitude of the Arctic-related variability mode. Future work using multi-model ensembles, transient forcing experiments, and isotope-enabled simulations will be essential to further constrain the relative roles of internal variability and external forcing.

Overall, this study demonstrates that multi-centennial AMOC variability emerges from robust internal ocean processes whose expression depends on the background climate state. These results underscore the importance of internal variability for understanding past climate fluctuations and caution against attributing low-frequency climate signals solely to external forcing. As greenhouse-gas concentrations continue to rise, internal ocean dynamics are likely to remain a significant, though evolving, contributor to long-term climate variability.

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Data availability. Due to the extremely large size of the output raw data from EC-Earth3 simulations, these files were not deposited in a public repository, but are available from the corresponding author upon reasonable request.

REFERENCES

- Askjær, T. G., et al. Multi-centennial Holocene climate variability in proxy records and transient model simulations. *Quat. Sci. Rev.* 296, 107801; <https://doi.org/10.1016/j.quascirev.2022.107801> (2022).
- Ahluwalia, H. S., Ygbuhay, R. C. Salient features of the new sunspot number time series. *Sol. Phys.* 291, 3807-3815 (2016).
- Bakker, P., Clark, P. U., Golledge, N. R., Schmittner, A. & Weber, M. E. Centennial-scale Holocene climate variations amplified by Antarctic Ice Sheet discharge. *Nature*, 541 (7635), 72-76; <https://doi.org/10.1038/nature20582> (2017).
- Batté, L., Välisuo, I., Chevallier, M., Acosta Navarro, J. C., Ortega, P. & Smith, D. Summer predictions of Arctic sea ice edge in multi-model seasonal re-forecasts. *Clim. Dyn.* 54 (11), 5013-5029; <https://doi.org/10.1007/s00382-020-05273-8> (2020).
- Bellomo, K. & Mehling, O. Impacts and state - dependence of AMOC weakening in a warming climate. *Geophys. Res. Lett.* 51 (10), L107624; <https://doi.org/10.1029/2023GL107624> (2024).
- Berggren, A.-M., et al. A 600-year record of ^{10}Be and ^{14}C variations: Implications for solar and climate variability. *Geophys. Res. Lett.* 36 (11), L11801; <https://doi.org/10.1029/2009GL038004> (2009).
- Brodeau, L. & Koenigk, T. Extinction of the northern oceanic deep convection in an ensemble of climate model simulations of the 20th and 21st centuries. *Clim. Dyn.* 46 (9), 2863-2882; <https://doi.org/10.1007/s00382-015-2736-5> (2016).

- 607 Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G. & Saba, V. Observed fingerprint of
 608 a weakening Atlantic Ocean overturning circulation. *Nature*, 556 (7700), 191-196;
 609 <https://doi.org/10.1038/s41586-018-0006-5> (2018).
- 610 Cao, N., et al. The role of internal feedbacks in sustaining multi-centennial variability of
 611 the Atlantic Meridional Overturning Circulation revealed by EC-Earth3-LR
 612 simulations. *Earth Planet. Sci. Lett.* 621, 118372;
 613 <https://doi.org/10.1016/j.epsl.2023.118372> (2023).
- 614 Cini, M., et al. Noise-shaped hysteresis cycles of the AMOC under increasing CO₂
 615 forcing. *Chaos*, 2025, 35(2), 023167; <https://doi.org/10.1063/5.0241503> (2025).
- 616 Colin de Verdière, A., Ben Jelloul, M. & Sévellec, F. Bifurcation structure of
 617 thermohaline millennial oscillations. *J. Clim.* 19 (22), 5777-5795;
 618 <https://doi.org/10.1175/JCLI3950.1> (2006).
- 619 Danabasoglu, G. On multidecadal variability of the Atlantic Meridional Overturning
 620 Circulation in the Community Climate System Model Version 3. *J. Clim.* 21 (21),
 621 5524-5544; <https://doi.org/10.1175/2008JCLI2019.1> (2008).
- 622 Delworth, T. L. & Mann, M. E. Observed and simulated multidecadal variability in the
 623 Northern Hemisphere. *Clim. Dyn.* 16 (9), 661-676;
 624 <https://doi.org/10.1007/s003820000075> (2000).
- 625 Delworth, T. L. & Zeng, F. Multicentennial variability of the Atlantic meridional
 626 overturning circulation and its climatic influence in a 4000 year simulation of the
 627 GFDL CM2.1 climate model. *Geophys. Res. Lett.* 39 (13), L13702;
 628 <https://doi.org/10.1029/2012GL052107> (2012).
- 629 DeVries T. The ocean carbon cycle. *Annu. Rev. Environ. Resour.* 47, 317-341 (2022).

- 630 Dima, M., Lohmann, G., Ionita, M., Knorr, G. & Scholz, P. AMOC modes linked with
631 distinct North Atlantic deep water formation sites. *Clim. Dyn.* 59 (3), 837-849;
632 <https://doi.org/10.1007/s00382-022-06156-w> (2022).
- 633 Döscher, R., et al. The EC-Earth3 Earth system model for the Coupled Model
634 Intercomparison Project 6. *Geosci. Model Dev.* 15 (7), 2973-3020;
635 <https://doi.org/10.5194/gmd-15-2973-2022> (2022).
- 636 Ferster, B. S., Subramanian, A. & Zanna, L. The climate-state dependence of AMOC
637 variability in a warming world: Insights from paleo and modern constraints. *J. Clim.*
638 38 (2), 451-467; <https://doi.org/10.1175/JCLI-D-24-0156.1> (2025).
- 639 Friedrich, T., Timmermann, A., Menviel, L., Elison Timm, O., Mouchet, A. & Roche, D.
640 M. The mechanism behind internally generated centennial-to-millennial scale
641 climate variability in an earth system model of intermediate complexity. *Geosci.*
642 *Model Dev.* 3 (2), 377-389; <https://doi.org/10.5194/gmd-3-377-2010> (2010).
- 643 Hasselmann, K. Stochastic climate models: Part I. Theory. *Tellus A.* 28 (6), 473-485;
644 <https://doi.org/10.3402/tellusa.v28i6.11316> (1976).
- 645 Hazeleger, W., et al. EC-Earth: A seamless earth-system prediction approach in action.
646 *Bull. Am. Meteorol. Soc.* 91 (10), 1357-1364;
647 <https://doi.org/10.1175/2010BAMS2877.1> (2010).
- 648 Hazeleger, W., et al. EC-Earth V2.2: description and validation of a new seamless earth
649 system prediction model. *Clim. Dyn.* 39 (11), 2611-2629;
650 <https://doi.org/10.1007/s00382-011-1228-5> (2012).

- 651 He, J., Sun, W., Wang, B., et al. Multi-centennial variability of the Afro-Asian monsoon
 652 linked to Atlantic meridional overturning circulation. *Geophys. Res. Lett.*, 53,
 653 e2025GL119871. <https://doi.org/10.1029/2025GL119871> (2026).
- 654 Jiang, Z., et al. No consistent simulated trends in the Atlantic Meridional Overturning
 655 Circulation for the past 6000 years. *Geophys. Res. Lett.* 50 (10), e2023GL103078;
 656 <https://doi.org/10.1029/2023GL103078> (2023).
- 657 Jiang, W., Gastineau, G. & Codron, F. Multicentennial variability driven by salinity
 658 exchanges between the Atlantic and the Arctic Ocean in a coupled climate model. *J.*
 659 *Adv. Model Earth Syst.* 13 (3), e2020MS002366;
 660 <https://doi.org/10.1029/2020MS002366> (2021).
- 661 Knudsen, M. F., et al. Evidence of Suess solar-cycle bursts in subtropical Holocene
 662 speleothem δ 18O records. *Holocene*. 22 (5), 597-602 (2012).
- 663 Li, C., von Storch, J.-S. & Marotzke, J. Deep-ocean heat uptake and equilibrium climate
 664 response. *Clim. Dyn.*, 40 (5), 1071-1086; <https://doi.org/10.1007/s00382-012-1350-z>
 665 (2013).
- 666 Li, G., et al. Increasing ocean stratification over the past half-century. *Nat. Clim. Change*.
 667 10 (12), 1116-1123; <https://doi.org/10.1038/s41558-020-00918-2> (2020).
- 668 Li, Y. & Yang, H. A theory for self-sustained multicentennial oscillation of the Atlantic
 669 Meridional Overturning Circulation. *J. Clim.* 35 (18), 5883-5896;
 670 <https://doi.org/10.1175/JCLI-D-21-0685.1> (2022).
- 671 Liu, C., et al. Discrepancies in simulated ocean net surface heat fluxes over the North
 672 Atlantic. *Adv. Atmos. Sci.* 39 (11), 1941-1955; [https://doi.org/10.1007/s00376-022-](https://doi.org/10.1007/s00376-022-1360-7)
 673 1360-7 (2022).

- 674 Ma, L. H., Vaquero, J. M. Is the Suess cycle present in historical naked-eye observations
675 of sunspots?. *New Astron.* 14 (3), 307-310 (2009).
- 676 Mann, M. E., et al. Global signatures and dynamical origins of the Little Ice Age and
677 Medieval Climate Anomaly. *Science*. 326 (5957), 1256-1260;
678 <https://doi.org/10.1126/science.1177303> (2009).
- 679 Mann, M. E., Steinman, B. A. & Miller, S. K. On forced temperature changes, internal
680 variability, and the AMO. *Geophys. Res. Lett.* 41 (9), 3211-3219;
681 <https://doi.org/10.1002/2014GL059233> (2014).
- 682 Mann, M. E., Steinman, B. A., Brouillette, D. J. & Miller, S. K. Multidecadal climate
683 oscillations during the past millennium driven by volcanic forcing. *Science*, 371
684 (6533), 1014-1019; <https://doi.org/10.1126/science.abc5810> (2021).
- 685 Martin, T., Park, W. & Latif, M. Multi-centennial variability controlled by Southern
686 Ocean convection in the Kiel Climate Model. *Clim. Dyn.* 40 (7), 2005-2022;
687 <https://doi.org/10.1007/s00382-012-1586-7> (2013).
- 688 Martin, T., Park, W. & Latif, M. Southern Ocean forcing of the North Atlantic at multi-
689 centennial time scales in the Kiel Climate Model. *Deep Sea Res. Part II.* 114, 39-48,
690 <https://doi.org/10.1016/j.dsr2.2014.01.018> (2015).
- 691 Meccia, V. L., et al. Internal multi-centennial variability of the Atlantic Meridional
692 Overturning Circulation simulated by EC-Earth3. *Clim. Dyn.* 59 (9), 2685-2701;
693 <https://doi.org/10.1007/s00382-022-06534-4> (2022).
- 694 Menary, M. B., et al. A multimodel comparison of centennial Atlantic meridional
695 overturning circulation variability. *Clim. Dyn.* 38 (11), 2377-2388;
696 <https://doi.org/10.1007/s00382-011-1172-4> (2012).

- 697 Mehling, O., Bellomo, K., Angeloni, M., Pasquero, C. & von Hardenberg, J. High-
 698 latitude precipitation as a driver of multicentennial variability of the AMOC in a
 699 climate model of intermediate complexity. *Clim. Dyn.* 59 (9), 2721-2735;
 700 <https://doi.org/10.1007/s00382-022-06640-3> (2022).
- 701 Moffa-Sánchez, P., et al. Variability in the Northern North Atlantic and Arctic Oceans
 702 across the last two millennia: A review. *Paleoceanogr. Paleoclimatol.* 34 (8), 1399-
 703 1436; <https://doi.org/10.1029/2018PA003508> (2019).
- 704 Msadek, R. & Frankignoul, C. Atlantic multidecadal oceanic variability and its influence
 705 on the atmosphere in a climate model. *Clim. Dyn.* 33 (1), 45-62;
 706 <https://doi.org/10.1007/s00382-008-0452-0> (2009).
- 707 Otterå, O. H., Bentsen, M., Drange, H. & Suo, L. External forcing as a metronome for
 708 Atlantic multidecadal variability. *Nat. Geosci.* 3 (10), 688-694;
 709 <https://doi.org/10.1038/ngeo955> (2010).
- 710 Prange, M., et al. A multicentennial mode of North Atlantic climate variability
 711 throughout the Last Glacial Maximum. *Science advances*, 9(44):
 712 <https://doi.org/10.1126/sciadv.adh1106> (2023)
- 713 Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S. &
 714 Schaffernicht, E. J. Exceptional twentieth-century slowdown in Atlantic Ocean
 715 overturning circulation. *Nat. Clim. Change.* 5 (5), 475-480;
 716 <https://doi.org/10.1038/nclimate2554> (2015).
- 717 Richard, J. G. A Possible Connection between the de Vries Cycle and the Solar Dynamo.
 718 *Sol. Phys.* 297 (9), 124 (2022).

- 719 Rivin, I. & Tziperman, E. Linear versus self-sustained interdecadal thermohaline
 720 variability in a coupled box model. *J. Phys. Oceanogr.* 27 (7), 1216-1232;
 721 [https://doi.org/10.1175/1520-0485\(1997\)027<1216:LVSSIT>2.0.CO;2](https://doi.org/10.1175/1520-0485(1997)027<1216:LVSSIT>2.0.CO;2) (1997).
- 722 Sicre, M.-A., et al. A 4500-year reconstruction of sea surface temperature variability at
 723 decadal time-scales off North Iceland. *Quat. Sci. Rev.* 27 (21), 2041-2047;
 724 <https://doi.org/10.1016/j.quascirev.2008.08.009> (2008).
- 725 Suess H E. The radiocarbon record in tree rings of the last 8000 years. *Radiocarbon.* 22
 726 (2), 200-209 (1980).
- 727 Sun, W., Liu, J., Wang, B., Chen, D., Wan, L. & Wang, J. Holocene multi-centennial
 728 variations of the Asian Summer Monsoon triggered by solar activity. *Geophys. Res.*
 729 *Lett.* 49 (13), e2022GL098625; <https://doi.org/10.1029/2022GL098625> (2022).
- 730 Taricco, C., et al. A high-resolution $\delta^{18}\text{O}$ record and Mediterranean climate variability.
 731 *Clim. Past*, 11, 509 – 522; <https://doi.org/10.5194/cp-11-509-2015> (2015).
- 732 Vellinga, M. & Wu, P. Low-latitude freshwater influence on centennial variability of the
 733 Atlantic thermohaline circulation. *J. Clim.* 17 (23), 4498-4511;
 734 <https://doi.org/10.1175/3219.1> (2004).
- 735 Vermassen, F., et al. A seasonally ice-free Arctic Ocean during the Last Interglacial. *Nat.*
 736 *Geosci.* 16 (8), 723-729; <https://doi.org/10.1038/s41561-023-01227-x> (2023).
- 737 Welander, P. A simple heat-salt oscillator. *Dynam. Atmos. oceans.* 6 (4), 233-242;
 738 [https://doi.org/10.1016/0377-0265\(82\)90030-6](https://doi.org/10.1016/0377-0265(82)90030-6) (1982).
- 739 Yang, K., Yang, H., Li, Y. & Zhang, Q. North Atlantic Ocean-originated multicentennial
 740 oscillation of the AMOC: a coupled model study. *J. Clim.* 37 (9), 2789-2807;
 741 <https://doi.org/10.1175/JCLI-D-23-0422.1> (2024).

- Yeager, S. & Danabasoglu, G. The origins of late-twentieth-century variations in the large-scale North Atlantic circulation. *J. Clim.* 27 (9), 3222-3247; <https://doi.org/10.1175/JCLI-D-13-00125.1> (2014).
- Zampieri, L., Goessling, H. F. & Jung, T. Bright prospects for Arctic sea ice prediction on subseasonal time scales. *Geophys. Res. Lett.* 45 (18), 9731-9738; <https://doi.org/10.1029/2018GL079394> (2018).
- Zhang, R., et al. A review of the role of the Atlantic Meridional Overturning Circulation in Atlantic multidecadal variability and associated climate impacts. *Rev. Geophys.* 57 (2), 316-375; <https://doi.org/10.1029/2019RG000644> (2019).
- Zhang, R., Follows, M. & Marshall, J. Mechanisms of thermohaline mode switching with application to warm equable climates. *J. Clim.* 15 (15), 2056-2072; [https://doi.org/10.1175/1520-0442\(2002\)015<2056:MOTMSW>2.0.CO;2](https://doi.org/10.1175/1520-0442(2002)015<2056:MOTMSW>2.0.CO;2). (2002).
- Zhang, R. Northward intensification of anthropogenically forced changes in the Atlantic Meridional Overturning Circulation (AMOC). *Geophys. Res. Lett.* 37 (24), L24602; <https://doi.org/10.1029/2010GL045054> (2010).
- Zhao, J., Yang, H. & Zhang, J. Salinity-driven water mass transformation in the North Atlantic: Insights from NEMO-based model simulations. *Ocean Dyn.* 74 (6), 521-536; <https://doi.org/10.1007/s10236-024-01612-3> (2024).

**Supplementary material for “Climate-state
dependence of multi-centennial variability in
the Atlantic Meridional Overturning
Circulation”**

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Table S1. Trends of surface air temperature (SAT) and ocean temperature (OT) over the final 2000-model years. Units: °C per century.

Experiments	SAT	OT (0–200 m)	OT (0–200 m)	OT (0–200 m)
E280	0.02	0.01	0.01	0.01
E400	0.02	0.01	0.02	0.02
E560	0.02	0.01	0.03	0.03

in press

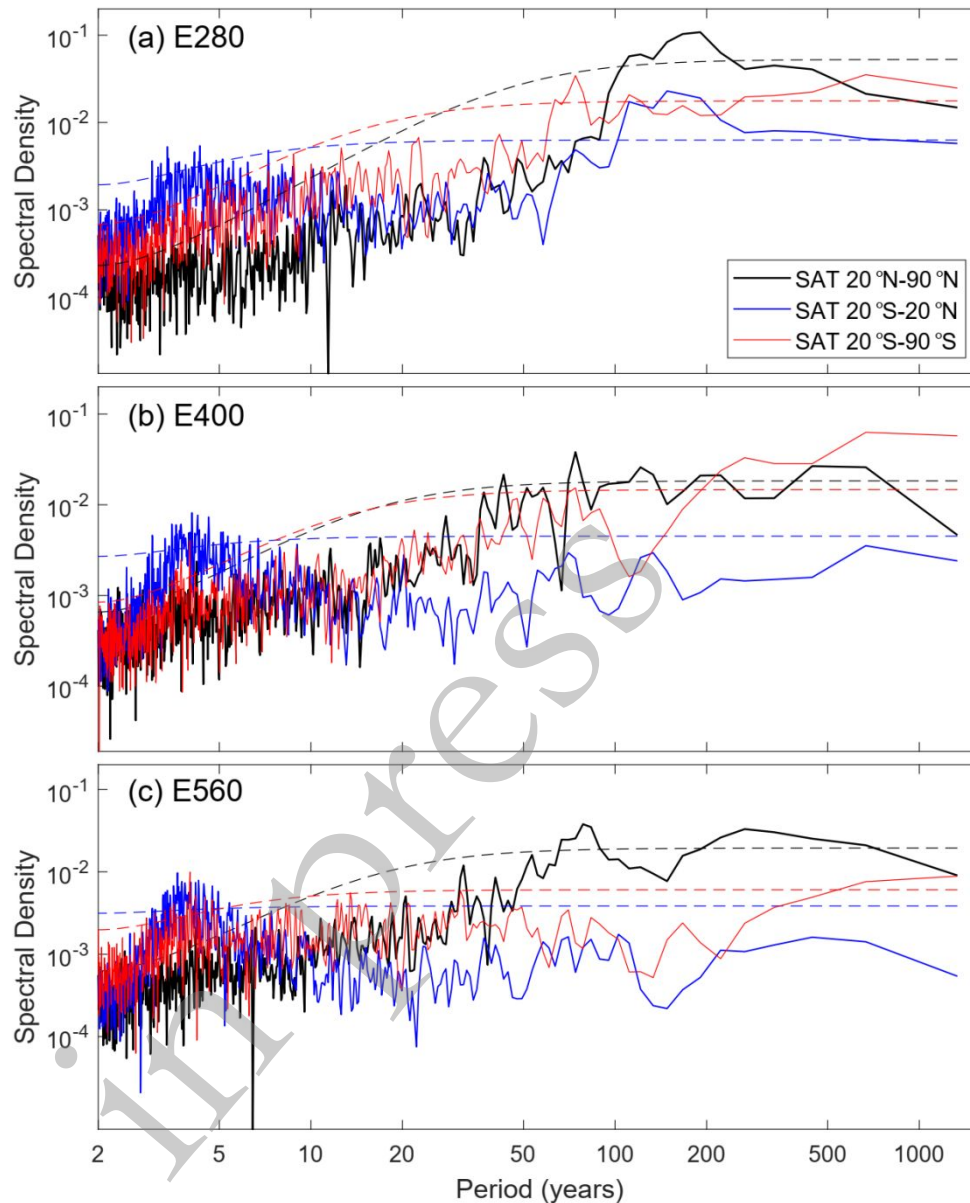


Fig. S1 Spectra of the regional mean surface air temperature (SAT) time series in three simulations. Black curves indicate latitudinal band from 20°N to north pole (Northern Hemisphere extratropical region), blue curves indicate latitudinal band from 20°S to 20°N (tropical region), and red curves indicate latitudinal band from 20°S to south pole (Southern Hemisphere extratropical region). The dashed curves indicate the 95% confidence level following the red noise background.

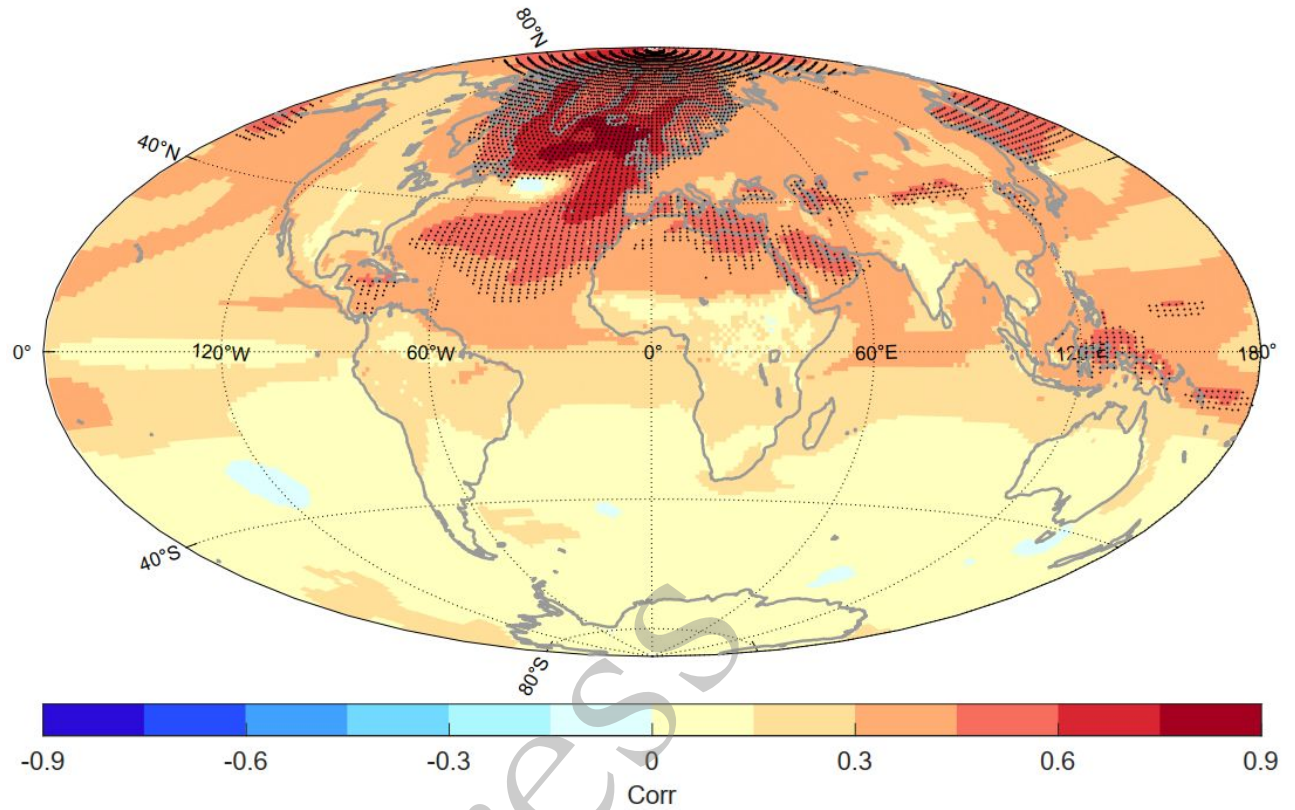


Fig. S2 Spatial correlations between annual mean SAT and the low-pass-filtered GMSAT (100-year cutoff) for E280 simulation. Dotted area indicates correlations exceeding the 95% confidence level.

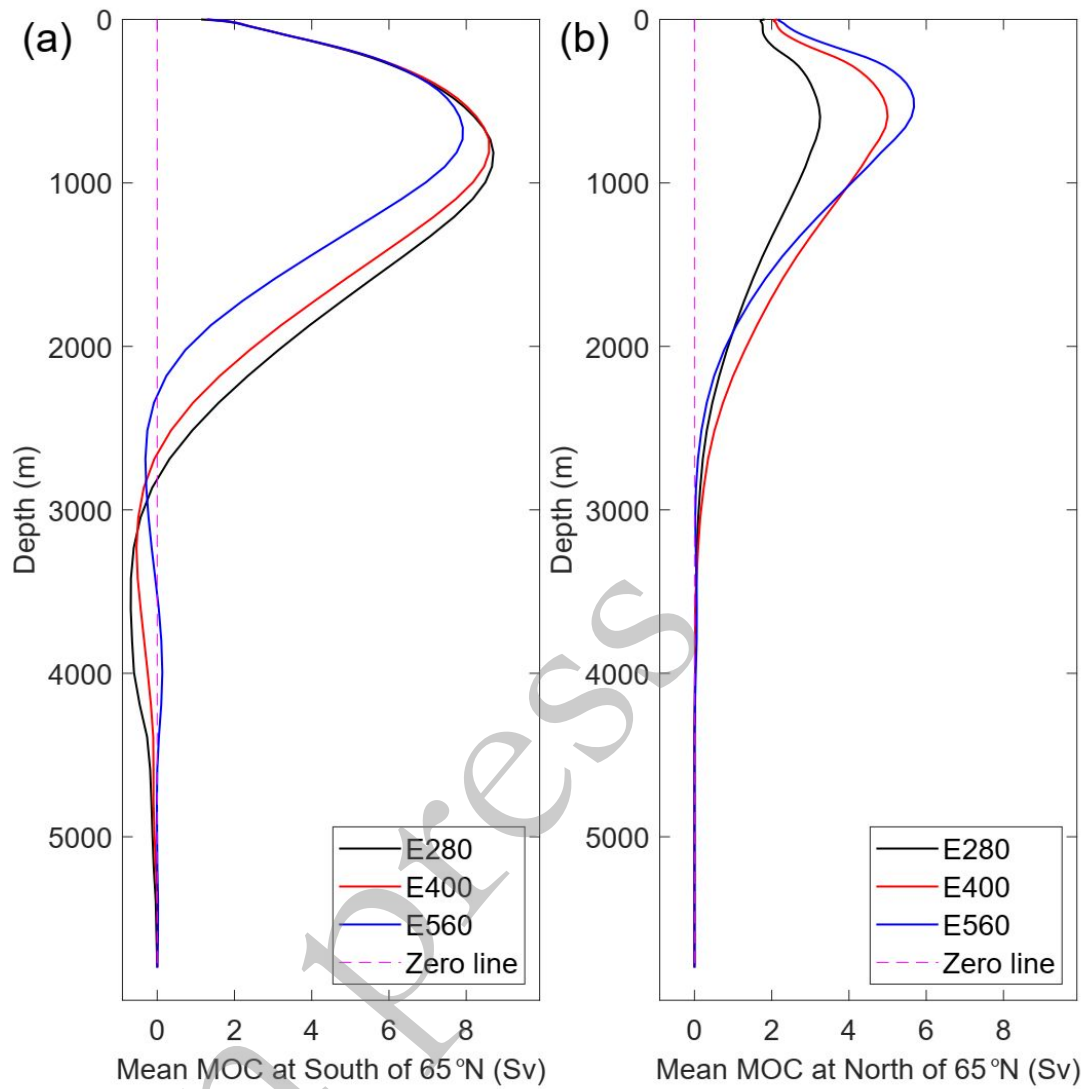


Fig. S3 The vertical profile of mean Meridional Overturning Circulation (MOC). (a) MOC at the south of 65°N and (b) north of 65°N in the North Atlantic-Arctic basins.

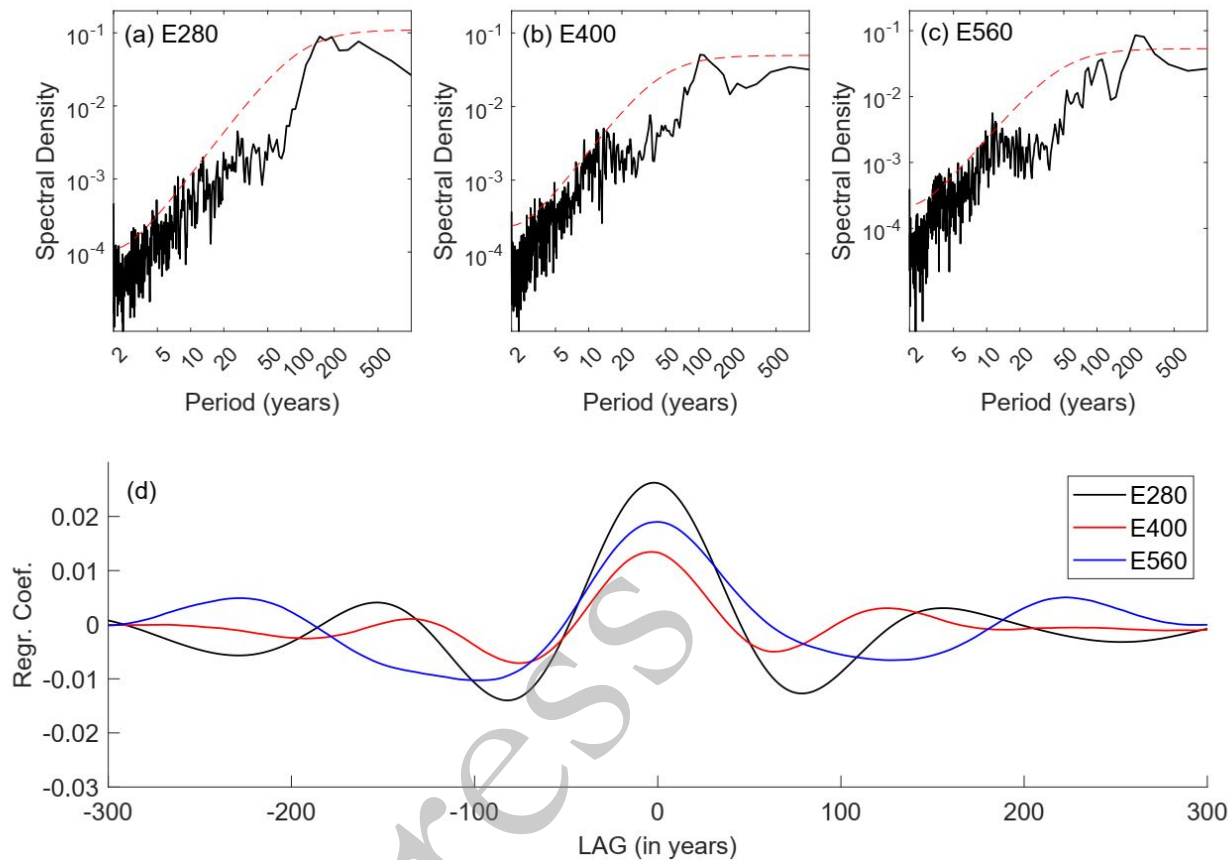


Fig. S4 The spectra of sea water potential density averaged in NADWF box for three experiments. (a) E280, (b) E400 and (c) E560; (d) The NADWF box mean sea water potential density [kg m^{-3}] regressed onto the low-pass filtered maximum AMOC index [Sv].

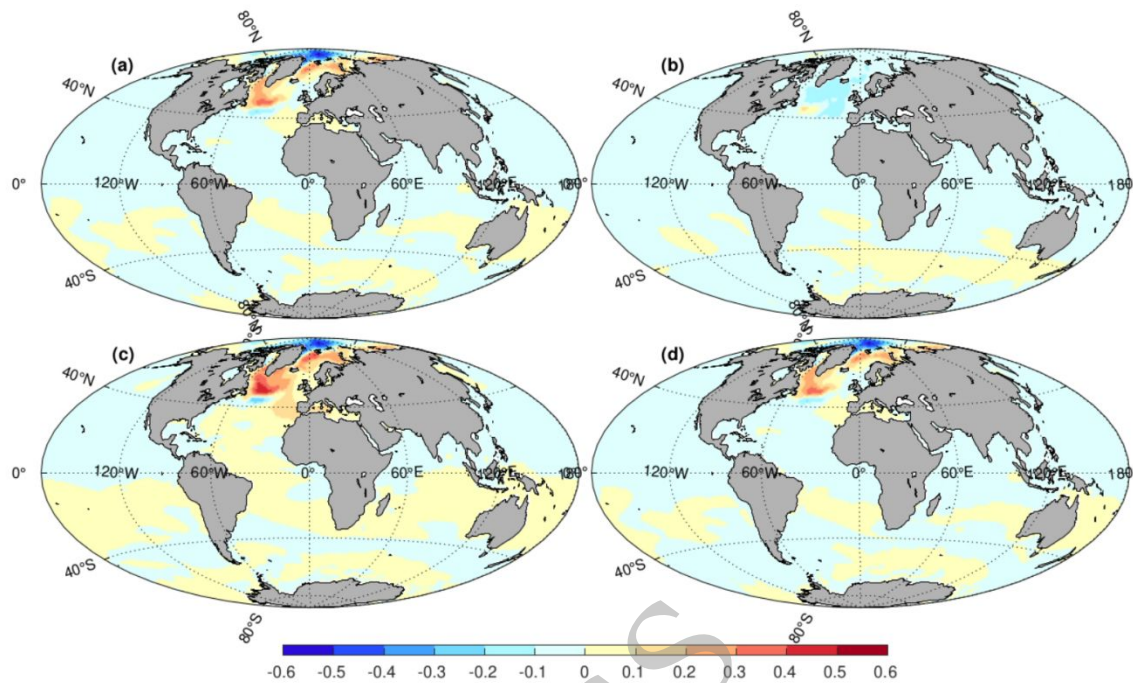


Figure S5. Regression of surface layer (a) seawater density, (b) temperature-induced density change, (c) salinity-induced density change and (d) the combined effect of temperature and salinity induced density changes, onto the low-pass filtered AMOC series. Units: kg m⁻³ per Sv.

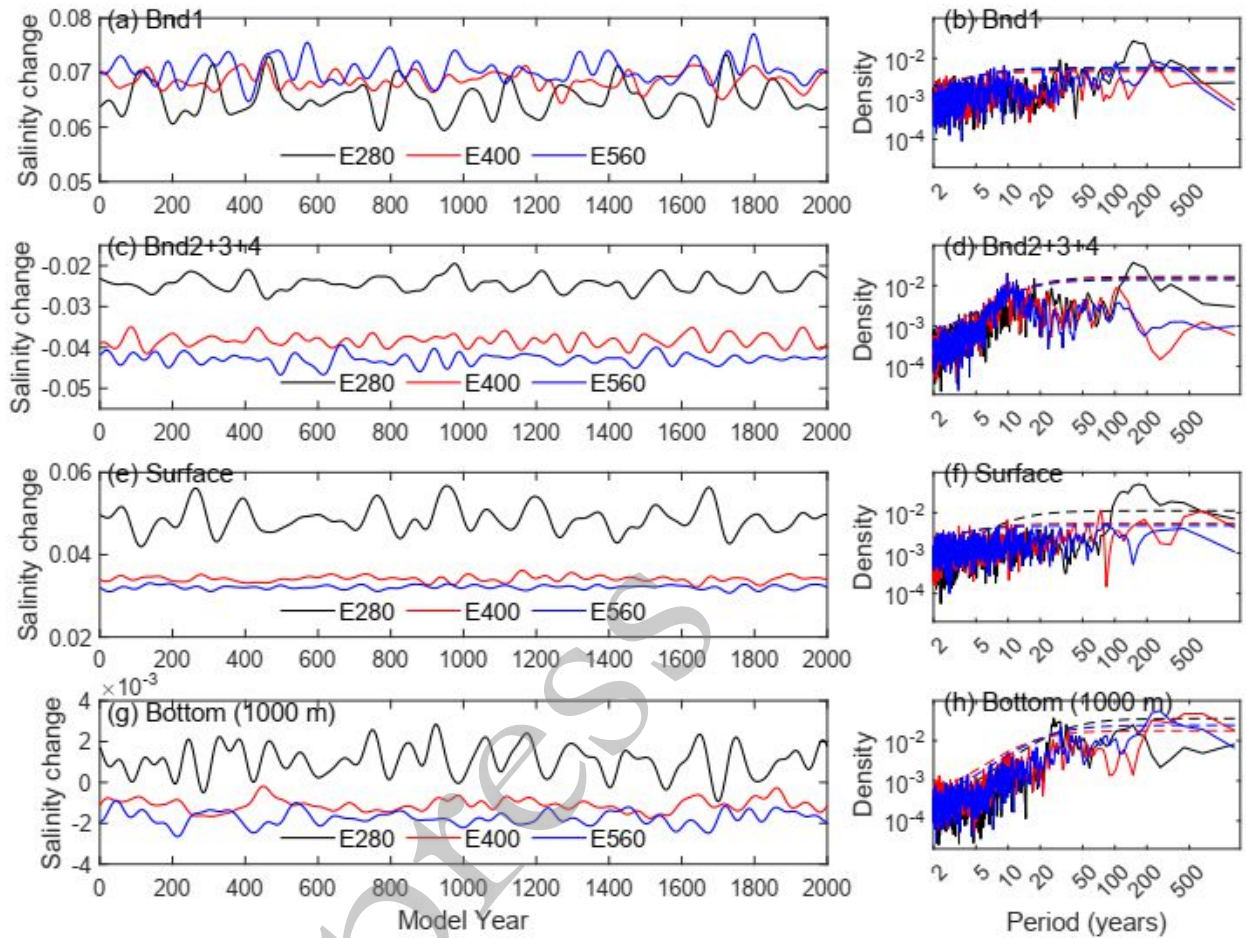


Fig. S6 Salinity changes of North Atlantic Deep-Water Formation (NADWF) box induced by external salt/freshwater fluxes. (a) Fluxes from the subtropical North Atlantic through boundary 1 at 45 °N , (c) from the Arctic Ocean through boundaries 2, 3, 4, (e) Fluxes from the surface, and (g) from the bottom face at about 1000 m. (b,d,f,h) The spectral density of these time series.

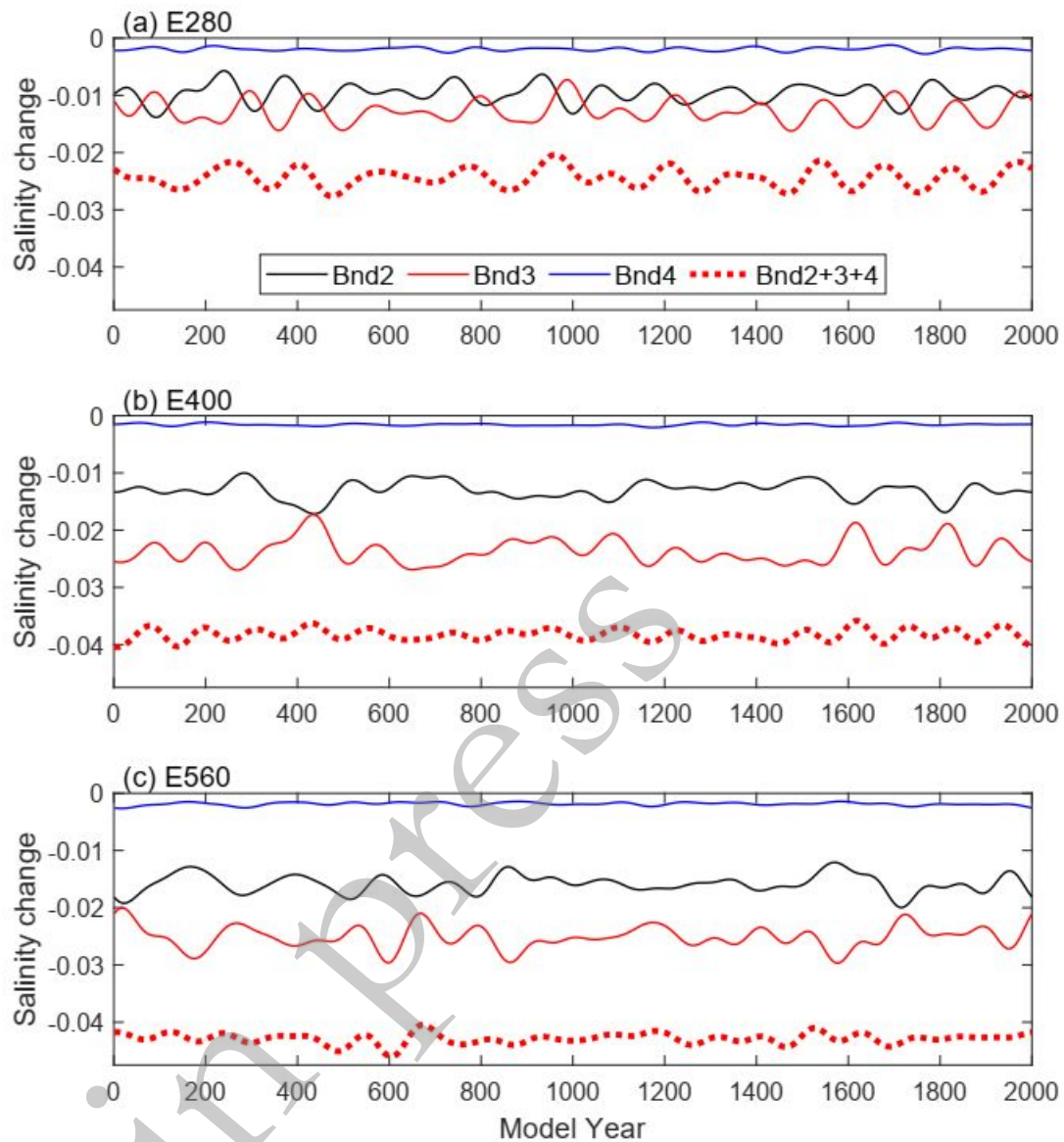


Fig. S7 Salinity changes of NADWF box induced by three Arctic boundaries (shown in Figure 5b) in three experiments. (a) E280, (b) E400, and (c) E560.