



North Atlantic jet stream responses to AMOC tipping and global warming in regional climate simulations

Alejandro Hermoso^{1,2}, Lucas Ferreira Correa³, Casey R. Patrizio⁴, Henk Dijkstra⁴, Anna von der Heydt⁴, and Christoph C. Raible^{1,2}

¹Climate and Environmental Physics, University of Bern, Bern, Switzerland

²Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

³Department of Geography, LMU Munich, Munich, Germany

⁴Institute for Marine and Atmospheric Research Utrecht (IMAU), Utrecht University, Utrecht, the Netherlands

Correspondence: Alejandro Hermoso (alejandro.hermoso@unibe.ch)

Abstract. European weather variability is largely influenced by the position and intensity of the North Atlantic (NA) jet stream. Understanding how the NA jet may respond to global warming and an additional potential collapse of the Atlantic Meridional Overturning Circulation (AMOC) is therefore essential for assessing future European climate. Here, we investigate these changes using two fully coupled Earth System Models (MPI-ESM-HR and CESM1) together with high-resolution regional dynamical downscaling. Global warming is simulated by increasing atmospheric CO₂ until a global mean warming of 2 K is reached, while AMOC collapse is induced through freshwater hosing from this 2 K state.

The regional simulations retain the main characteristics of the large-scale jet response simulated by the driving ESMs, while revealing regional modifications in both winter and summer that are more pronounced in summer. Under global warming, the response is highly model dependent, with an equatorward displacement of the winter jet in the MPI-driven simulations and a poleward displacement in the CESM-driven simulations. Following AMOC collapse, these contrasting responses persist, with the MPI-driven simulations retaining an equatorward-displaced jet and the CESM-driven simulations exhibiting a marked jet intensification.

These contrasting circulation changes arise from differences in the simulated AMOC response to global warming. MPI simulates substantially stronger AMOC weakening than CESM, leading to a more pronounced North Atlantic warming hole and stronger Arctic amplification. The resulting differences in sea surface temperature modify the meridional temperature gradients and baroclinicity, providing a physical explanation for the contrasting jet responses. Our results demonstrate that uncertainty in the simulated AMOC response propagates to regional atmospheric circulation and highlight the added value of regional dynamical downscaling for assessing the impacts of AMOC weakening and collapse on the North Atlantic jet stream.

1 Introduction

The North Atlantic eddy-driven jet stream plays a key role in European weather variability and the occurrence of extreme events, including cold and heat waves, heavy precipitation, and strong winds (Röthlisberger et al., 2016; Galfi and Messori,

2023). Understanding how the jet stream may respond to anthropogenic climate change is therefore a major research challenge, with important implications for future regional climate and weather extremes (Shaw and Miyawaki, 2024; Ossó et al., 2025).

Jet streams are commonly classified as either subtropical or midlatitude eddy-driven. Subtropical jets are maintained by the transport of angular momentum by the Hadley circulation and are generally confined to the upper troposphere (Krishnamuti, 1961). In contrast, eddy-driven jets are sustained by the growth of baroclinic transient eddies and the associated convergence of eddy momentum fluxes, which counteracts surface friction and allows the jet to extend throughout the troposphere (Hoskins et al., 1983; Vallis, 2017). Baroclinicity, which measures the potential for transient eddy growth (Charney, 1947; Eady, 1949), increases with a stronger meridional temperature gradient and a weaker vertical temperature gradient. Through the thermal wind balance, the meridional temperature gradient is proportional to the vertical wind shear, while the vertical temperature gradient is proportional to atmospheric stability.

Anthropogenic climate change influences these temperature gradients through two competing mechanisms that have opposing effects on the North Atlantic eddy-driven jet. Enhanced warming at high latitudes, known as Arctic amplification, weakens the meridional temperature gradient and has been proposed as a mechanism capable of modifying the jet stream (Barnes and Screen, 2015). However, recent studies suggest that its contribution to long-term jet stream trends is relatively weak (Blackport and Screen, 2020; Anderson et al., 2025). Conversely, increased latent heating in the tropical upper troposphere, resulting from the larger moisture-holding capacity of a warmer atmosphere according to the Clausius–Clapeyron relationship, partially offsets adiabatic cooling during ascent. This strengthens the upper-level meridional temperature gradient, favouring a stronger and more poleward jet stream (Woollings et al., 2023). Consequently, future changes in the North Atlantic jet depend on the balance between lower-level Arctic warming and upper-level tropical warming (Shaw et al., 2016). The relative importance of these competing processes remains a major source of uncertainty in future jet stream projections (Peings et al., 2018).

Beyond the direct effects of global warming, anthropogenic climate change may trigger abrupt and potentially irreversible transitions in components of the Earth system. Such components are referred to as climate tipping elements, while the rapid transition between alternative stable states can occur due to the presence of tipping points (Lenton et al., 2008; Armstrong McKay, 2024). One of the most prominent tipping elements is the Atlantic Meridional Overturning Circulation (AMOC), which could substantially weaken or even collapse as a consequence of ocean warming and freshening. Freshwater input from ice melt reduces the density of North Atlantic surface waters, suppressing deep convection and weakening the overturning circulation (van Westen et al., 2025a). Evidence that the AMOC exhibits tipping behaviour comes from theoretical studies (van Westen et al., 2025b), paleoclimate reconstructions of past AMOC collapses (Garity and Lund, 2024), and numerical modelling experiments (Pöppelmeier et al., 2023; Gerber et al., 2025).

The climatic consequences of an AMOC collapse have primarily been investigated using surface freshwater-forcing ("hosing") experiments in global climate models (Orihuela-Pinto et al., 2022; Jackson et al., 2023; Ma et al., 2024). These simulations indicate widespread cooling over Europe, particularly at high latitudes, together with a substantial reduction in precipitation (Jackson et al., 2015; Liu et al., 2020; Bellomo et al., 2023; van Westen et al., 2024; van Westen and Baatsen, 2025). However, these studies have largely relied on relatively coarse-resolution global climate models. The response of the North Atlantic jet stream to the combined effects of global warming and an AMOC collapse has not yet been systematically investigated using



higher-resolution regional climate model simulations. Increased resolution can reduce important biases present in global models, such as an overly zonal and equatorward North Atlantic jet, which are partly linked to deficiencies in the representation of diabatic processes (Schemm, 2023).

60 Here, we use a dynamical downscaling framework to analyse simulations from two Earth System Models (ESMs) under multiple climate scenarios in order to quantify the response of the North Atlantic eddy-driven jet to both global warming and an AMOC collapse. Specifically, we address the following research questions:

- How does the regional downscaling modify the simulated jet stream compared with the driving global ESM simulations?
- How do global warming and an AMOC collapse affect the North Atlantic jet stream, and what physical mechanisms
- 65 explain these changes?
- How robust are these responses across the two different ESMs?

The remainder of the paper is structured as follows: Section 2 describes global and regional climate simulation, the different scenarios considered and the analysis techniques used. Section 3 presents the North Atlantic jet stream responses to global warming and imposed AMOC collapse, and sections 4 and 5 provide a discussion of the results and conclusions, respectively.

70 2 Models and Methods

Dynamical downscaling simulations are performed using the Weather Research and Forecasting (WRF) model version 4.6.0 (Skamarock et al., 2019). This section describes the driving ESM simulations, the experimental design, the WRF configuration, and the diagnostics used to analyse changes in the North Atlantic jet stream.

2.1 Driving data and experimental setup

75 The regional climate simulations are driven by two ESM simulations, performed with the MPI-ESM-HR (Müller et al., 2018) and CESM1-CAM5 (Meehl et al., 2013) models. The atmospheric component of MPI-ESM-HR has a horizontal resolution of $0.935^\circ \times 0.9375^\circ$ with 95 vertical levels. The land component of MPI-ESM-HR, JSBACH3.2/3.20 (Mauritsen et al., 2019), uses the same horizontal grid as the atmospheric component, represents different plant functional types through a tiled structure, and has dynamic vegetation turned off. The ocean component, MPIOM1.6.3 (Jungclaus et al., 2013), uses an eddy-permitting

80 tripolar grid with a nominal horizontal resolution of 0.4° and 40 unevenly spaced vertical levels. The atmospheric component of CESM1 (CAM5) has a horizontal resolution of $0.942^\circ \times 1.25^\circ$ with 30 vertical levels. The land component of CESM1, CLM4.0, (Lawrence et al., 2011), uses the same horizontal grid as the atmospheric model and was run with prescribed satellite phenology, without an interactive carbon–nitrogen cycle. The ocean component, POP2 (Danabasoglu et al., 2012), used a nominal 1° Greenland displaced-pole curvilinear horizontal grid (gx1v6) with 60 vertical levels.

85 The experimental design is summarised in Table 1. First, 100-year periods are selected from equilibrated, multicentury pre-industrial control simulations (piC) with constant pre-industrial radiative forcings. These simulations maintain a global mean

surface air temperature of approximately 14°C (blue lines in Fig. 1a,c) and an AMOC strength at 26°N of approximately 20 Sv in CESM1 and 17 Sv in MPI-ESM-HR (blue lines in Fig. 1b,d).

To investigate the impact of global warming, an additional experiment is conducted in which the atmospheric CO₂ concentration is increased by 1% per decade (pink lines in Fig. 1a,c). During this transient warming phase, the AMOC weakens slightly in CESM1, reaching approximately 17 Sv, and more substantially in MPI-ESM-HR, decreasing to approximately 13 Sv (pink lines in Fig. 1b,d). Once the 30-year averaged global mean surface temperature reaches 2 K, the atmospheric CO₂ concentration is decreased to maintain a stable global mean warming level of 2 K (stable_T2K; yellow lines in Fig. 1) following the Method P discussed in Wood et al. (2026).

To investigate the impact of an AMOC collapse, a hosing experiment was performed (stable_T2K_AMOC) by branching from the beginning of the stable_T2K simulation. The hosing experiment followed NaHosMIP Jackson et al. (2023), in which 0.3 Sv hosing was uniformly applied to the subpolar North Atlantic and Arctic over a period of 100 years. This resulted in a strong weakening of the AMOC strength to approximately 5 Sv in both models (green lines in Fig. 1b,d). Hereafter, we refer to the weak AMOC state obtained through freshwater hosing as the collapsed AMOC state. The AMOC weakening is accompanied by a decrease in global mean surface temperature relative to the stable_T2K simulation (green lines in Fig. 1a,c).

Experiment	Description
piControl	Pre-industrial forcing
1pctCO2	Ramp-up period increasing CO ₂ concentration at a rate of 1% per year
stable_T2K	Stable global warming of 2 K after 1pctCO2
stable_T2K_AMOC	AMOC collapse imposed through hosing on top of the stable_T2K scenario

Table 1. Overview of the different ESM (MPI-ESM-HR and CESM1) simulations used in this study.

2.2 WRF downscaling

The ESM simulations described in the previous subsection are dynamically downscaled using WRF over a domain covering Europe and a large portion of the North Atlantic (Fig. 2). The simulations are driven by the ESM outputs described in the previous section, with lateral boundary conditions updated every 6 h.

The model is configured with a horizontal grid spacing of 15 km, 50 terrain-following η levels extending up to 50 hPa, which closely follow the topography near the surface and gradually transition to constant pressure surfaces at higher levels, and four soil layers reaching a depth of 2 m. An adaptive time step is used for the numerical integration, and model output is archived at hourly intervals. The physical parameterisations include the WSM microphysics scheme (Hong and Lim, 2006), the RRTMG

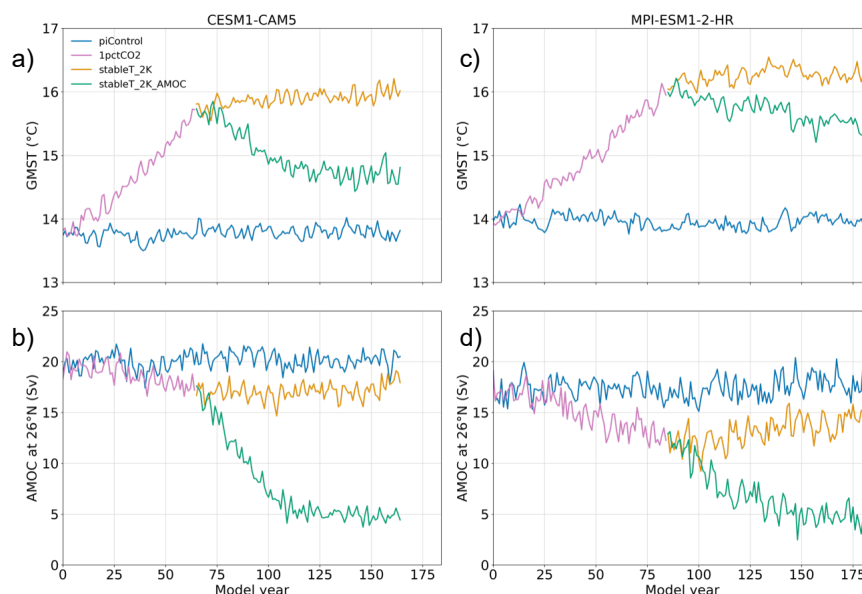


Figure 1. Time series of a), c) global mean surface air temperature and b), d) AMOC strength at 26° N in CESM1 (a, b) and MPI-ESM1-2-HR (c,d) for the different experiments: piControl, ramp-up 1pctCO₂, stable_T2K and stable_T2K_AMOC.

radiation scheme (Iacono et al., 2008), the MM5 Monin–Obukhov surface layer scheme (Fairall et al., 2003; Jiménez et al., 2012), the Noah-MP land surface model (Niu et al., 2011), the MYNN planetary boundary layer scheme (Nakanishi and Niino, 2006), and the Kain–Fritsch cumulus parameterisation (Kain, 2004).

For the piControl, stable_T2K and stable_T2K_AMOC experiments (Table 1) and for each driving ESM, a corresponding 22-year WRF simulation is performed using the last part of the ESM simulations. The first two years are discarded as spin-up, leaving 20 years for the analysis of the impacts of global warming and AMOC collapse.

The simulations store the major meteorological variables at hourly resolution. Vertically, the data is interpolated to 14 pressure levels: 1000, 950, 900, 850, 800, 750, 700, 600, 500, 400, 300, 250, 200, 100 hPa.

2.3 Analysis of the baroclinicity: Isentropic slope

The slope of the isentropic surfaces is analysed as a measure of baroclinicity and to interpret changes in the jet stream. The isentropic slope is closely related to the growth of baroclinic waves (Van Delden, 1999; Papritz and Spengler, 2015), which develop when the average slope of air parcel trajectories is smaller than the isentropic slope (Green, 1960). The isentropic slope

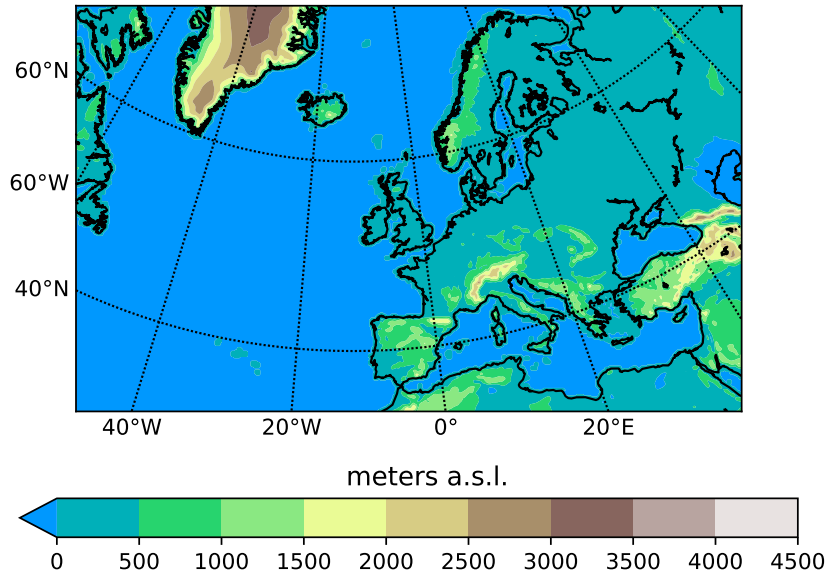


Figure 2. Domain used for the WRF regional downscaling simulations at 15 km horizontal grid spacing.

is defined as:

$$S = \frac{\frac{\partial \theta}{\partial y}}{\frac{\partial \theta}{\partial p}}, \quad (1)$$

where θ is the potential temperature, y denotes the meridional direction, and p is pressure. The WRF output is interpolated to pressure levels, and S is calculated at hourly intervals. Seasonal means are then computed over the 20-year analysis period for each experiment to quantify changes in baroclinicity.

2.4 Jet regimes

Following Frame et al. (2011), the North Atlantic jet stream is characterised using the low-level zonal wind between 925 and 700 hPa. The zonal wind is first vertically averaged over these pressure levels and subsequently zonally averaged over the North Atlantic (60°W–0°). Using the low-level wind isolates the eddy-driven jet, which has a predominantly barotropic structure (Hoskins et al., 1983), while minimising the influence of the subtropical jet, which is generally confined to the upper levels.

A k -means clustering algorithm is applied to this mean meridional zonal wind profile to classify the jet into three regimes at each hourly time step. The clustering is performed independently for each season (DJF and JJA). The algorithm identifies three



cluster centroids and assigns each hourly jet profile to the nearest centroid by minimising the Euclidean distance between the
 135 profile and the corresponding centroid. The three regimes are labelled south ("S"), middle ("M"), and north ("N") according
 to the latitudinal position of their respective centroids. The choice of three clusters follows previous studies (Woollings et al.,
 2010; Frame et al., 2011), which demonstrated that this classification provides a robust representation of the principal modes
 of variability of the North Atlantic jet stream.

2.5 Statistical significance

140 Significance of the zonal wind changes is tested with a standard two-sample student *t*-test at a level of 5% given their variability
 within the 20 years. We use the false discovery rate (Wilks, 2016) to assess the significance. We define a global *p*-value
 $p^* = \max[p_i \leq (i/N)\alpha]$, where p_i is the local *p*-value derived from the *t*-test sorted in ascending order, *N* is the number of
 grid points and $\alpha = 0.1$ is a chosen threshold. The differences are considered to be significant if the local *p*-value is lower than
 the global *p*-value.

3 Results

3.1 Impacts of global warming on the North Atlantic jet stream

The response of the 250-hPa zonal wind to 2 K global warming relative to pre-industrial conditions exhibits substantial differ-
 ences between the two driving ESMs during winter (Fig. 3). The MPI-ESM simulation shows a clear equatorward displacement
 of the North Atlantic jet (Fig. 3a), whereas the CESM simulation exhibits a tripolar pattern characterised by an increase in zonal
 150 wind speed on the northern and southern flanks of the climatological jet and a decrease near its mean position, consistent with
 a poleward displacement of the jet (Fig. 3b).

The regional simulations reproduce the large-scale responses of their driving models but with notable differences. The MPI-
 driven simulation maintains the equatorward displacement of the jet, although the response is less zonal and shifted downstream
 (Fig. 3c). In contrast, the CESM-driven simulation shows a predominantly poleward displacement of the jet, but without the
 155 reduction in zonal wind speed at higher latitudes present in the driving simulation (Fig. 3d).

During summer, the responses to stable 2 K warming relative to pre-industrial conditions of the two ESMs also differ
 considerably. The MPI-ESM simulation shows enhanced zonal wind over the North Atlantic around Scandinavia and the British
 Isles, as well as over the south-western part of the domain, while weaker winds occur around the climatological jet position
 (Fig. 4a). In contrast, the CESM simulation exhibits a tripolar pattern, with reduced zonal wind south of the climatological jet
 160 and enhanced zonal wind on its northern and southern flanks (Fig. 4b).

The summer response in the MPI-driven regional simulation differs from its driving ESM by exhibiting a broad south-west
 to north-east band of enhanced zonal wind extending from the North Atlantic towards the Mediterranean, together with only a
 weak reduction around the climatological jet position (Fig. 4c). This contrasts with the tripolar pattern simulated by MPI-ESM
 (Fig. 4a). The CESM-driven regional simulation retains a tripolar structure, although most changes are concentrated near the

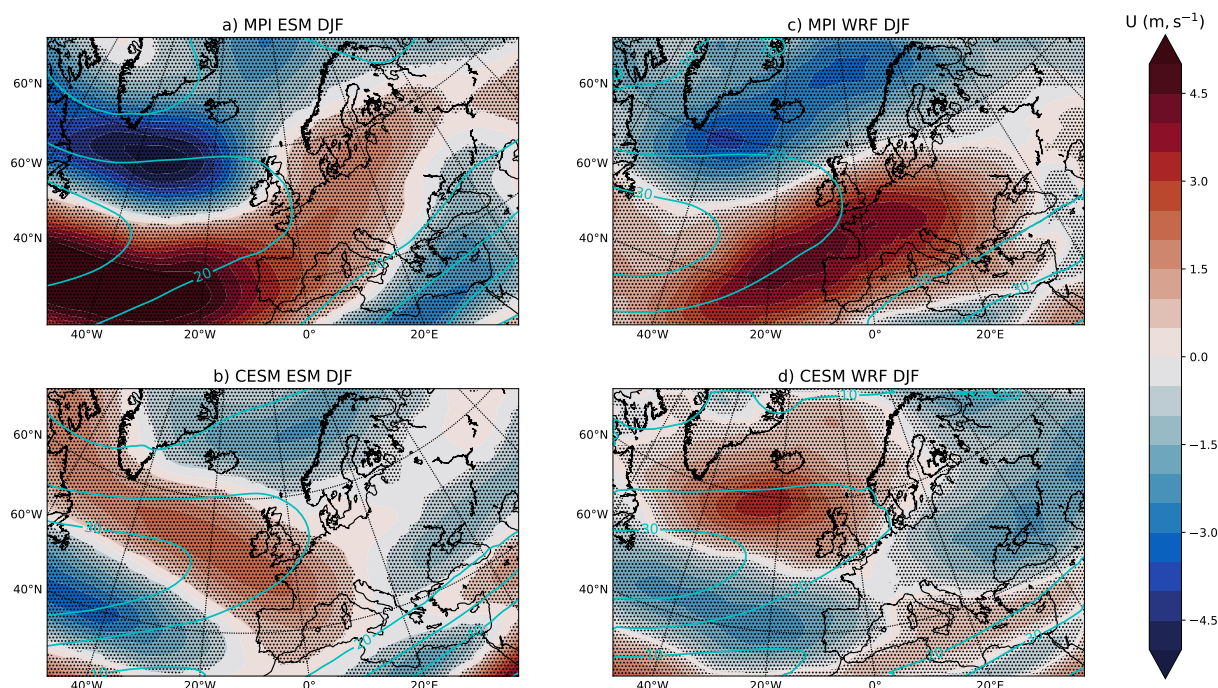


Figure 3. Difference in a), b) global ESM and c), d) WRF regionally downscaled winter (DJF) mean zonal wind speed at 250 hPa (shading) between stable_T2K and piControl for a), c) the MPI simulation and b), d) the CESM simulation. Blue contours (contour levels 10 m/s) depict the seasonal mean of zonal wind in the respective piControl simulation. Stippling indicates significant differences.

165 western boundary of the domain, where the influence of the lateral boundary conditions is strongest (Fig. 4d). Nevertheless, important regional differences emerge relative to the driving simulation, including enhanced zonal wind over the western Mediterranean and reduced zonal wind over Scandinavia, neither of which is present in the driving ESM.

The contrasting responses of the jet stream under 2 K global warming are reflected in the occurrence of the different jet regimes estimated for the dynamical downscaled simulations (orange bars in Fig. 5). In the MPI-driven regional simulation, the stable warming scenario is characterised by an increase in the frequency of the S regime and a decrease in the N regime during both winter and summer relative to piControl (blue bars in Fig. 5). By contrast, the CESM-driven simulation exhibits an increase in the frequency of the N regime in both seasons, accompanied by a reduction in the M regime during winter and in the S regime during summer. These changes in regime frequency are consistent with the mean zonal wind response discussed above, with the MPI-driven simulation favouring a more southerly jet and the CESM-driven simulation favouring a more northerly jet.

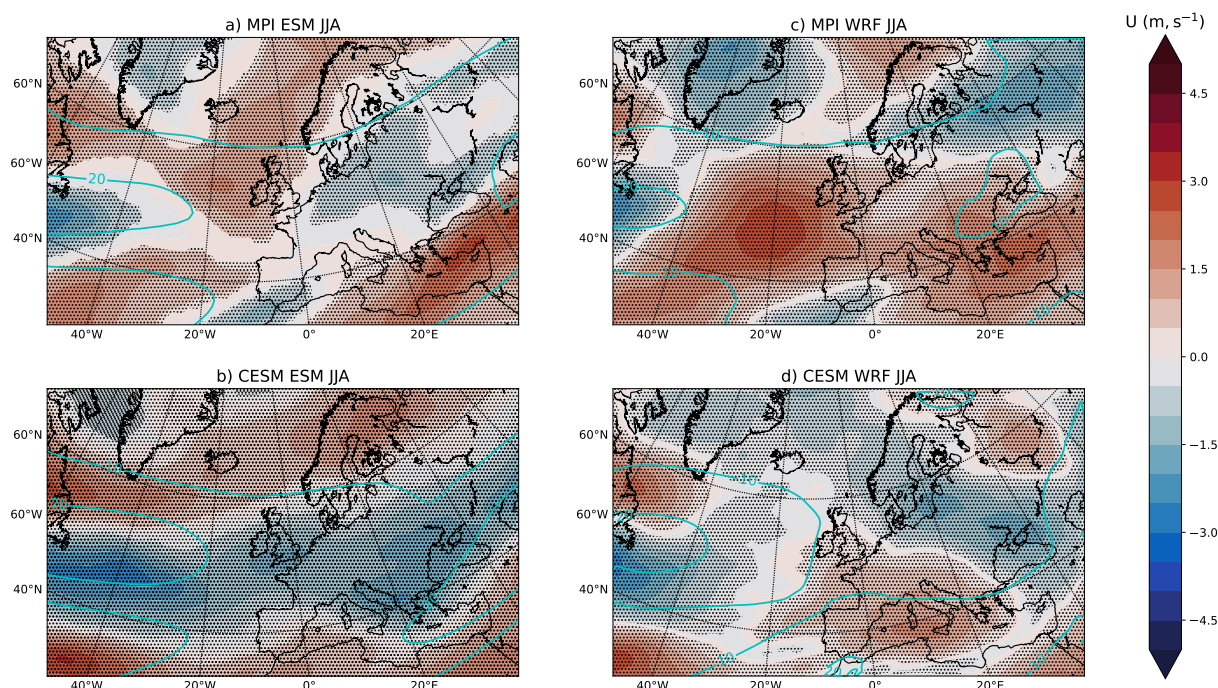


Figure 4. As in Fig. 3 for summer (JJA).

To investigate the mechanisms underlying the contrasting jet responses, we next examine the changes in sea surface temperature (SST) and geopotential height. The SST response reveals marked differences in both the strength of Arctic amplification and the location and intensity of the North Atlantic warming hole, a pattern previously identified in observations and climate simulations (Drijfhout et al., 2012). Arctic amplification is more pronounced in the MPI simulation (Fig. 6a) than in the CESM simulation (Fig. 6b). Additionally, the North Atlantic warming hole is stronger in the MPI simulation, consistent with the larger reduction in AMOC strength simulated by this model. During summer, the spatial patterns are broadly similar, although the North Atlantic warming hole is less pronounced in both simulations (Fig. 6c,d).

The geopotential height response also differs between the two simulations during winter. The MPI-driven simulation exhibits a region of relatively weak geopotential height increase over the central North Atlantic (Fig. 7a), centered on the transition between the positive and negative zonal wind anomalies shown in Fig. 3c. By contrast, the CESM-driven simulation shows a more spatially uniform increase in geopotential height (Fig. 7b). During summer, the geopotential height changes are comparatively uniform in both simulations (Fig. 7c,d).

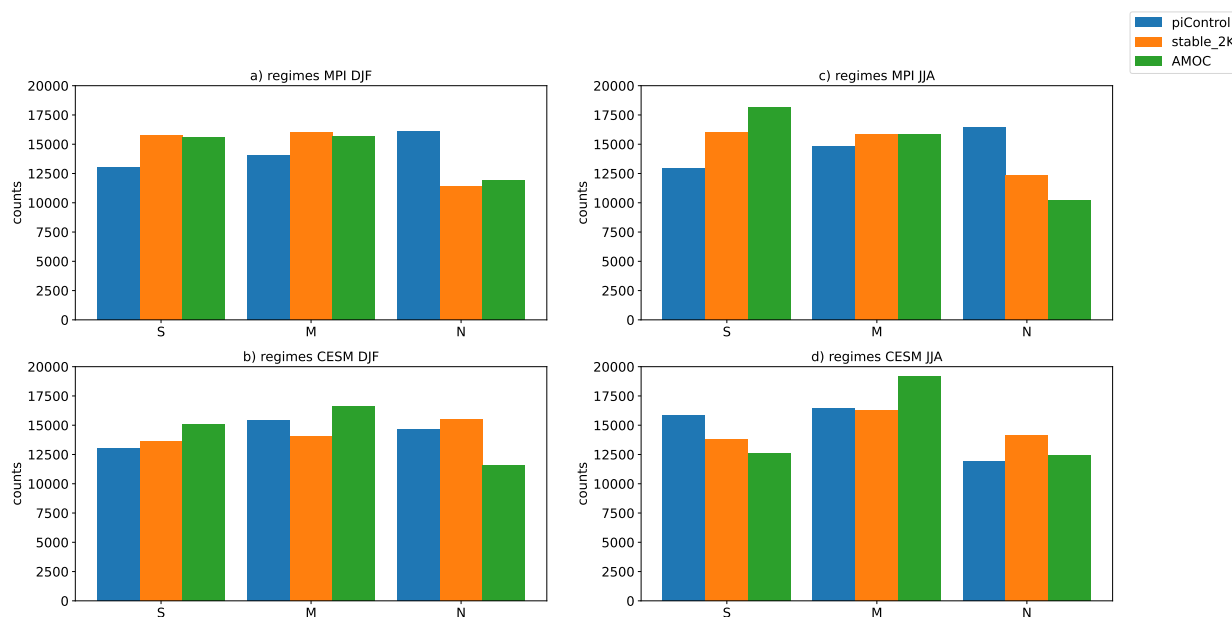


Figure 5. Frequency of the S, M and N regimes for each scenario: piControl (blue), stable_T2K (orange) and stable_T2K_AMOC (green) for the MPI-driven (a,c) and CESM-driven (b,d) regional WRF downscaling in winter (a,b) and summer (c,d).

The changes in zonal wind are accompanied by corresponding changes in baroclinicity, quantified by the isentropic slope (Fig. 8). In the MPI-driven simulation, the isentropic slope increases over the southern part of the domain, upstream of the upper-level wind increase and downstream of the lower-level wind increase, while a pronounced decrease is found at higher latitudes during winter (Fig. 8a,c). The CESM-driven simulation exhibits a northward displacement of the region of maximum baroclinicity in winter, together with a tripolar pattern at upper levels (Fig. 8b) and a widespread reduction in the isentropic slope at lower levels (Fig. 8d).

During summer, the MPI-driven simulation shows enhanced baroclinicity over the mid-latitudes and reduced baroclinicity between Greenland and Iceland (Fig. 9a,c). In the CESM-driven simulation, a tripolar pattern is evident over the North Atlantic, together with increased baroclinicity over the western Mediterranean (Fig. 9b,d). Overall, the spatial patterns of the isentropic slope closely resemble those of the zonal wind response.

In summary, the regional simulations broadly reproduce the large-scale circulation response of their driving ESMs, although important regional differences remain, particularly in the longitudinal structure of the jet response. The two ESMs exhibit contrasting changes in temperature gradients and baroclinicity, which are reflected in the distinct jet responses of the corresponding regional simulations.

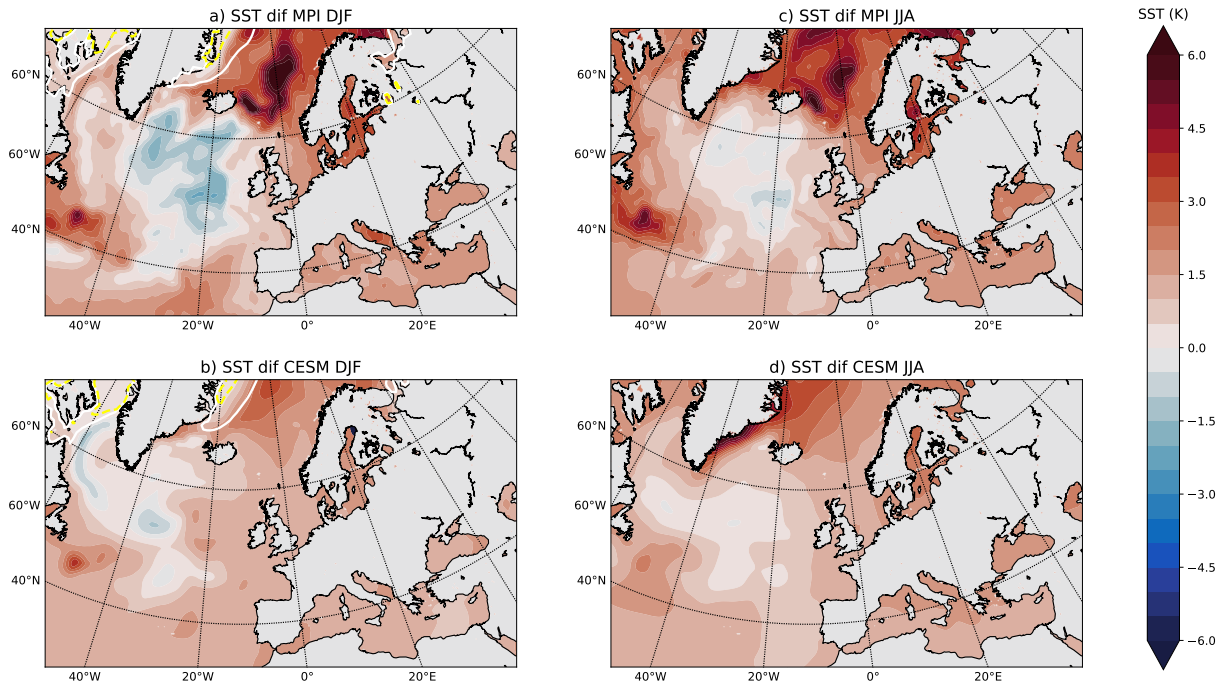


Figure 6. Difference in a), b) DJF and c), d) JJA mean sea surface temperature (shading) between the stable_T2K and the piControl experiments for a), c) the MPI global simulation and b), d) the CESM global simulation. The white and yellow contours in panels a) and b) represent the 60 % sea ice concentration in the piControl and stable_T2K simulations respectively.

3.2 Impacts of AMOC collapse on the North Atlantic jet stream

Having characterised the response to global warming, we now investigate the additional impact of an AMOC collapse on the North Atlantic jet. During winter, the zonal wind response exhibits marked differences between the two ESMs (Fig. 10a,b), similar to those found for the global warming response. In the MPI-ESM simulation, the jet undergoes a pronounced equatorward displacement (Fig. 10a), resembling the response to global warming but with a larger amplitude. This response is reproduced in the corresponding regional simulation (Fig. 10c). In contrast, the CESM simulation exhibits an intensification and eastward extension of the jet towards the European continent (Fig. 10b), a response that is also captured by the corresponding regional simulation (Fig. 10d). A similar jet response is obtained when the AMOC collapse simulation is compared with either piControl simulation (not shown) or the stable_T2K (Fig. 10).

During summer, the response to AMOC collapse relative to the stable 2 K warming scenario is characterised by a tripolar pattern in both ESMs, with enhanced zonal wind slightly poleward of the climatological jet position (Fig. 11a,b). Still,

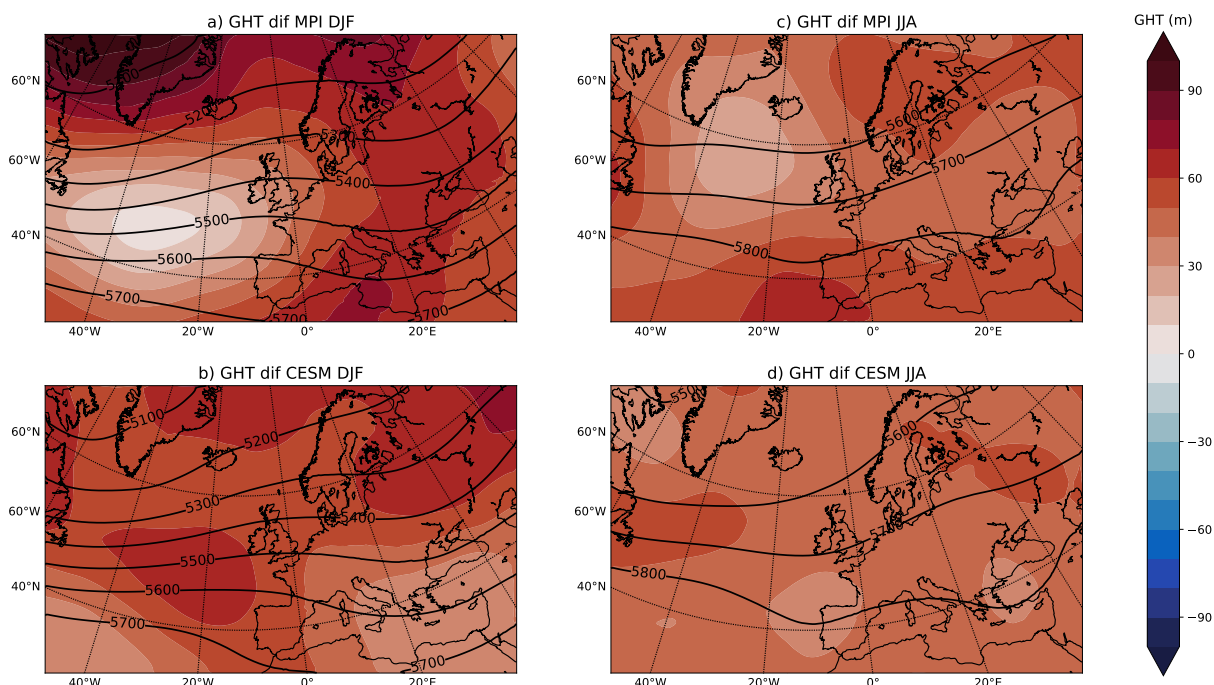


Figure 7. Difference in a), b) DJF and c), d) mean geopotential height at 500 hPa (shading) between the stable_T2K and the piControl simulations for a), c) the MPI-driven and b), d) the CESM-driven WRF downscaling. Black contours represent the seasonal mean of 500-hPa geopotential height in piControl.

the anomalies in the downscaling simulations are generally larger than in the driving ESMs, and the location of the jet intensification differs between the global and regional simulations, particularly in the CESM-driven case, where the region of jet intensification extends southwards towards the Iberian Peninsula in the regional simulation (Figs. 11b and 11d). In the MPI-driven regional simulation, the area of jet intensification is broadly consistent with that of the driving ESM, although the reduction in zonal wind equatorward of the climatological jet is stronger in the dynamical downscaled simulations than the driving ESM (Fig. 11c). The summer response therefore differs substantially between the MPI- and CESM-driven regional simulations.

As in the stable 2 K global warming simulations, we quantified changes in the occurrence of the different jet configurations for the AMOC collapse simulations (green bars in Fig. 5). During winter, the MPI-driven stable_T2K_AMOC regional simulation closely resembles the stable_T2K regional simulation, with an increased frequency of the S regime and a reduced

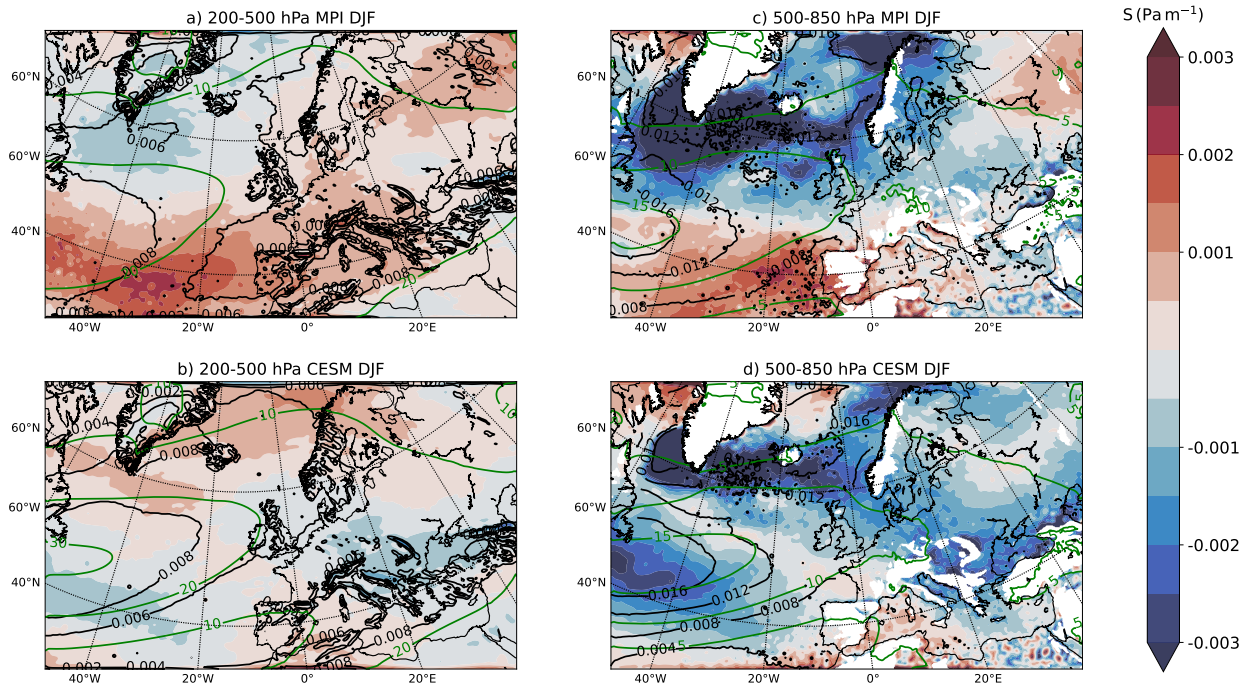


Figure 8. Difference in mean DJF isentropic slope (shading) averaged between a), b) 200 and 500 hPa and c), d) 500 and 850 hPa between the stable_T2K and the piControl simulations for a), c) the MPI-driven and b), d) the CESM-driven WRF downscaling. The black contours represent the seasonal mean of the isentropic slope averaged over the corresponding pressure levels, while the green contours show the mean zonal wind speed at 250 hPa in the respective piControl simulation. Areas with orography higher than 500 m are masked in panels c) and d).

frequency of the N regime (Fig. 5a). In contrast, the CESM-driven regional simulation exhibits an increase in the frequency of both the S and M regimes relative to both piControl and stable_T2K, accompanied by a reduction in the N regime (Fig. 5b).

225 During summer, the most pronounced changes occur in the CESM-driven regional simulation, where the frequency of the M regime increases at the expense of both the S and N regimes (Fig. 5d). The MPI-driven regional simulation exhibits comparatively smaller changes relative to stable_T2K (Fig. 5c).

To investigate the mechanisms underlying the contrasting jet responses, we examine the associated changes in SST. During winter, the SST response to AMOC collapse is characterised by pronounced cooling at high latitudes in both simulations, with mean temperature decreases exceeding 10 K in the CESM simulation and 5 K in the MPI simulation (Fig. 12a,b). The
 230 stronger cooling in the CESM simulation is consistent with the larger reduction in AMOC strength relative to the stable_T2K experiment.

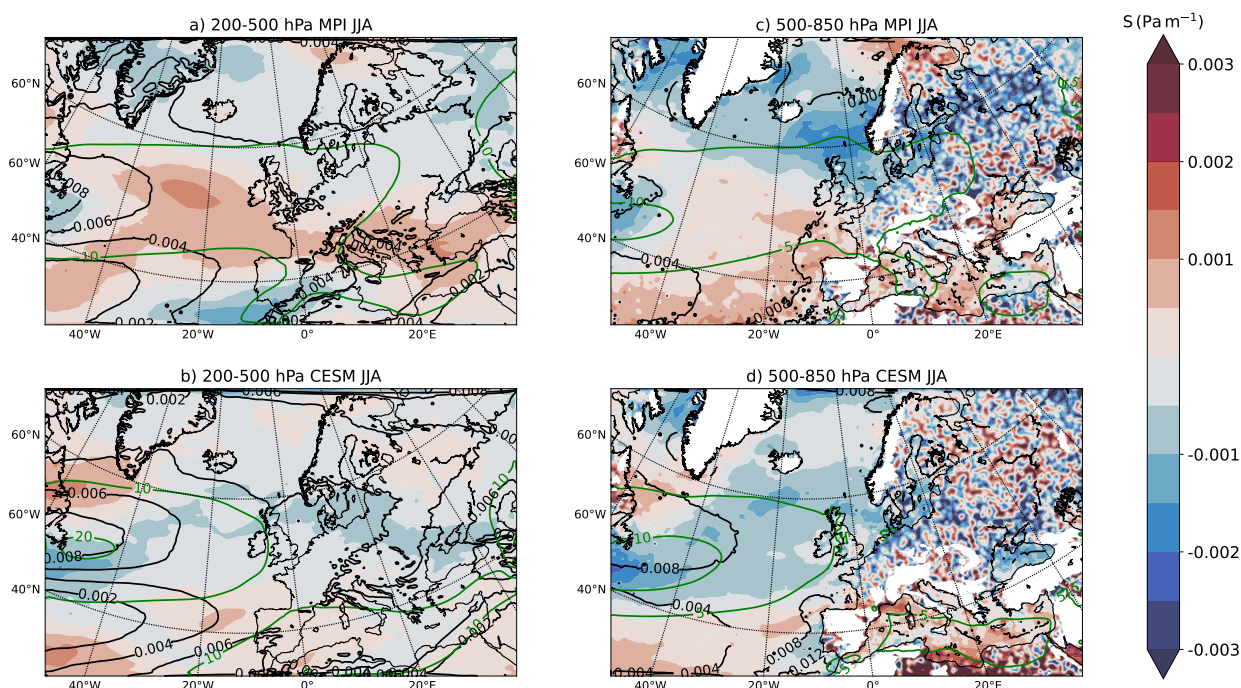


Figure 9. As in Fig. 8 for summer (JJA).

During summer, the spatial pattern of SST change is broadly similar in both simulations (Fig. 12c,d), with stronger cooling at high latitudes and weaker cooling over the southern part of the domain. In the MPI simulation, only weak SST anomalies are found north of Iceland relative to stable_T2K, reflecting the comparatively weak impact of AMOC collapse in this region together with the strong Arctic amplification present in the stable_T2K simulation. Consequently, the spatial pattern of the SST anomalies closely resembles that of the transition from piControl to stable_T2K, but with a larger amplitude, particularly over the North Atlantic warming hole.

The changes in the large-scale circulation are further illustrated by the geopotential height anomalies (Fig. 13). During winter, the MPI-driven simulation exhibits a pronounced reduction in geopotential height over the mid-latitude North Atlantic (Fig. 13a). In contrast, the CESM-driven simulation displays a dipolar pattern, characterised by a strong decrease in geopotential height at high latitudes and an increase over the central Mediterranean (Fig. 13b). During summer, the geopotential height anomalies are comparatively weak in the MPI-driven simulation (Fig. 13c). The CESM-driven simulation, however, exhibits a pronounced reduction in geopotential height south of Iceland (Fig. 13d), although the anomaly is weaker than during winter.

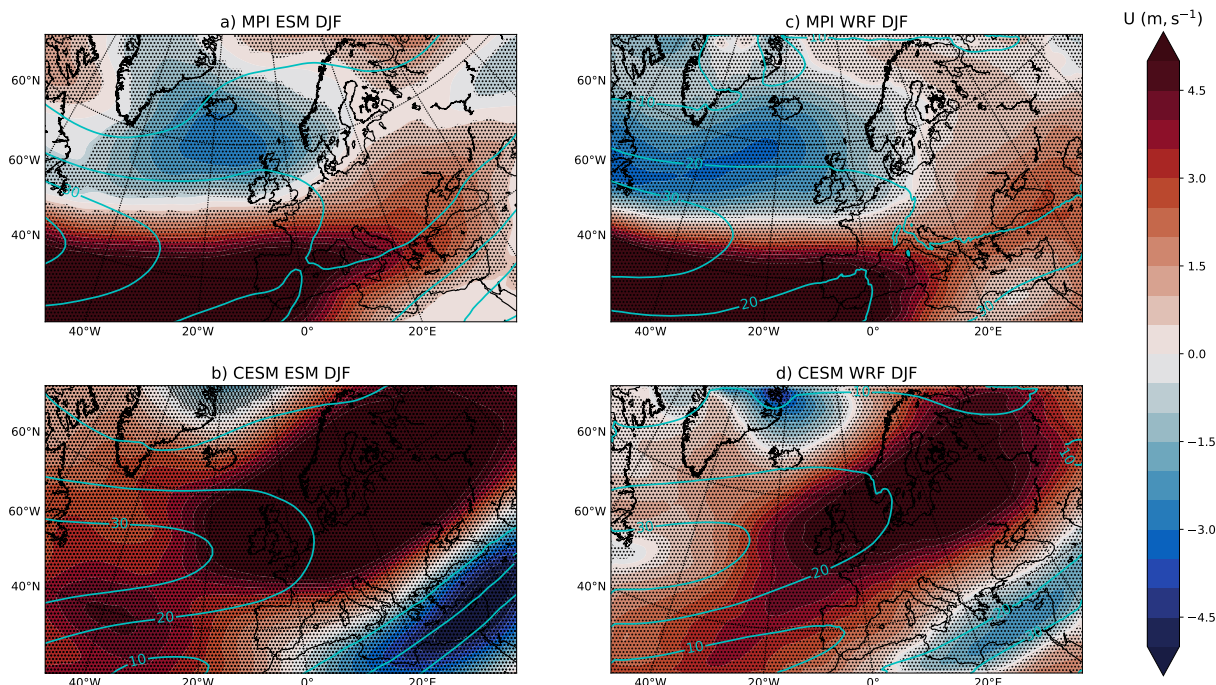


Figure 10. Winter zonal wind response at 250 hPa in a), b) global ESM and c), d) WRF regionally downscaled simulations (shading) and reference seasonally averaged zonal wind speed (black contours) between the stable_T2K_AMOC and stable_T2K for MPI-ESM-HR (a,c) and CESM1 (b,d). Stippling indicates significant differences.

245 Finally, we examine the changes in the isentropic slope to characterise the baroclinicity response to AMOC collapse (Figs. 14 and 15). During winter, the MPI-driven simulation exhibits increased baroclinicity over the southern part of the domain at both lower and upper levels (Fig. 14a,c), coinciding with the region of enhanced zonal wind south of the climatological jet position. In the CESM-driven simulation, baroclinicity increases along a southwest–northeast-oriented band at upper levels, while the increase is more widespread over the North Atlantic at lower levels (Fig. 14b,d). These regions broadly coincide with the
 250 positive zonal wind anomalies described above.

During summer, the MPI-driven simulation shows enhanced baroclinicity around 60°N, particularly at lower levels (Fig. 15a,c). In the CESM-driven simulation, baroclinicity increases around the British Isles, whereas a decrease is found over the northern part of the domain between Greenland and Scandinavia (Fig. 15b,d). A weaker reduction is also evident over the south-western corner of the regional domain at upper levels. The spatial patterns of the baroclinicity anomalies closely resemble those of the

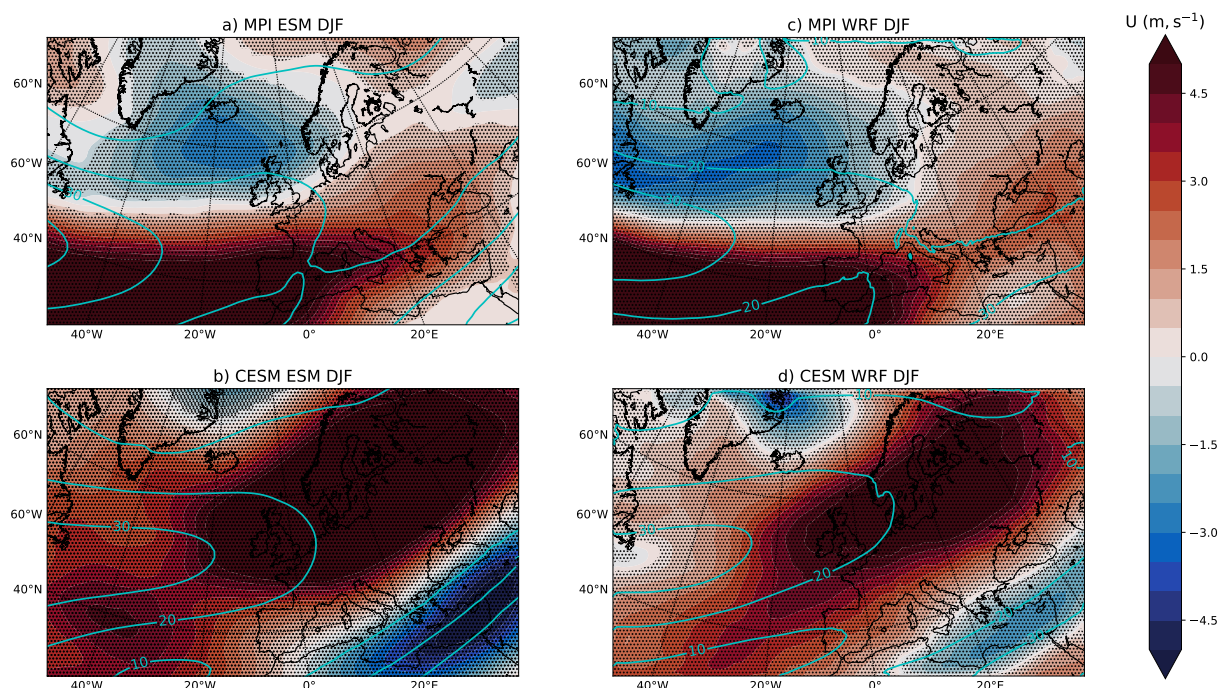


Figure 11. As in Fig. 10 for summer.

255 zonal wind changes, indicating that enhanced baroclinicity contributes to stronger zonal winds, while reduced baroclinicity contributes to weaker winds.

In summary, the response to an AMOC collapse exhibits the same model dependence identified for the global warming experiments. However, the circulation anomalies are generally larger following AMOC collapse. The CESM-driven simulation shows stronger high-latitude cooling and a more pronounced strengthening of the North Atlantic jet, whereas the MPI-driven simulation is characterised by an equatorward displacement of the jet and comparatively weaker thermodynamic changes.

260

4 Discussion

The results suggest that the response of the North Atlantic jet to global warming is highly influenced by the AMOC changes simulated by the driving ESMs. The contrasting behaviour can be understood in terms of the different AMOC responses under global warming simulated by the two models and the resulting changes in the North Atlantic SST pattern. Under pre-industrial conditions, the CESM simulation exhibits a stronger AMOC than MPI, but its circulation weakens less during the warming

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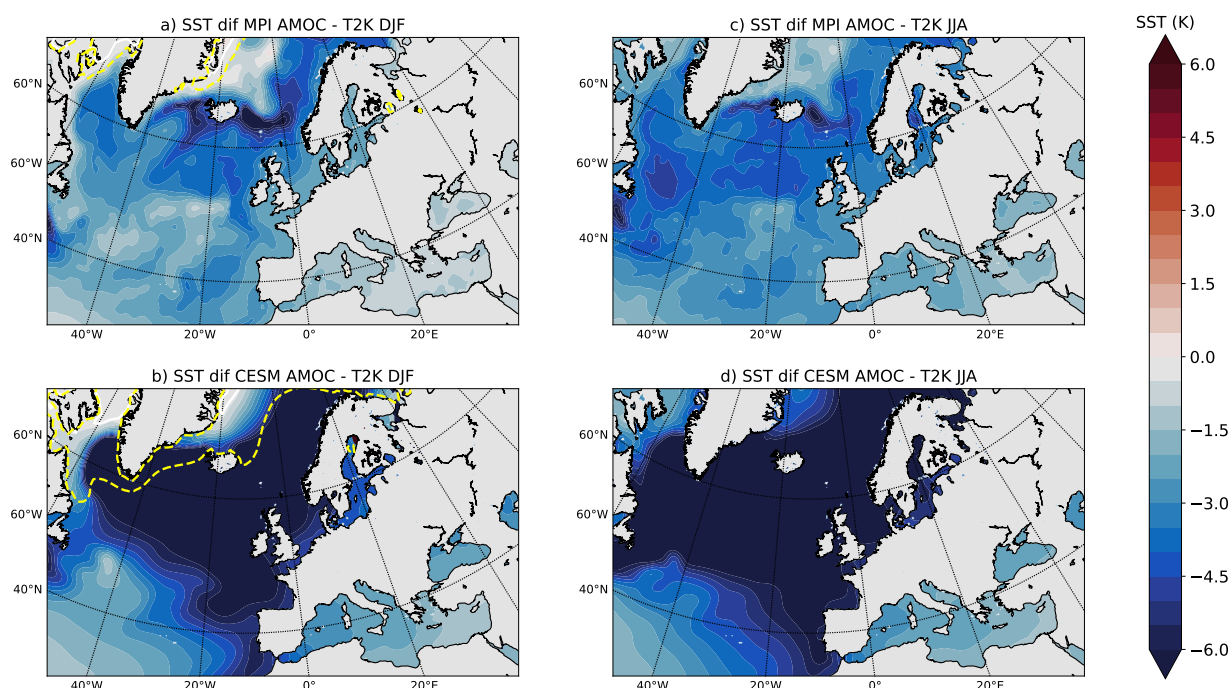


Figure 12. Difference in a), b) DJF and c), d) JJA mean sea surface temperature (shading) between the stable_T2K_AMOC and the stable_T2K experiments for a), c) the global MPI simulation and b), d) the global CESM simulation. The white and yellow contours in panels a) and b) represent the 60 % sea ice concentration in the piControl and stable_T2K simulations respectively.

experiment. Consequently, the SST change in CESM is characterised by a weaker North Atlantic warming hole, while Arctic amplification is also less pronounced than in MPI. In contrast, the greater sensitivity of the MPI AMOC to increasing global mean temperature produces a stronger North Atlantic warming hole (Liu et al., 2020; Li and Liu, 2025) together with enhanced Arctic amplification.

270 These distinct SST responses modify the meridional temperature gradients and the associated baroclinicity, providing a physical explanation for the different jet changes. In the MPI-driven simulation, the stronger Arctic amplification is consistent with an equatorward displacement of the winter jet, in agreement with previous studies (Butler et al., 2010; Peings et al., 2018). By contrast, the CESM-driven simulation shows a weaker Arctic amplification, which does not favour an equatorward shift of the jet as much as in the MPI-driven simulation. The MPI experiment therefore illustrates the atmospheric response
 275 to a moderate AMOC weakening of approximately 25% relative to the pre-industrial state, whereas the CESM simulation

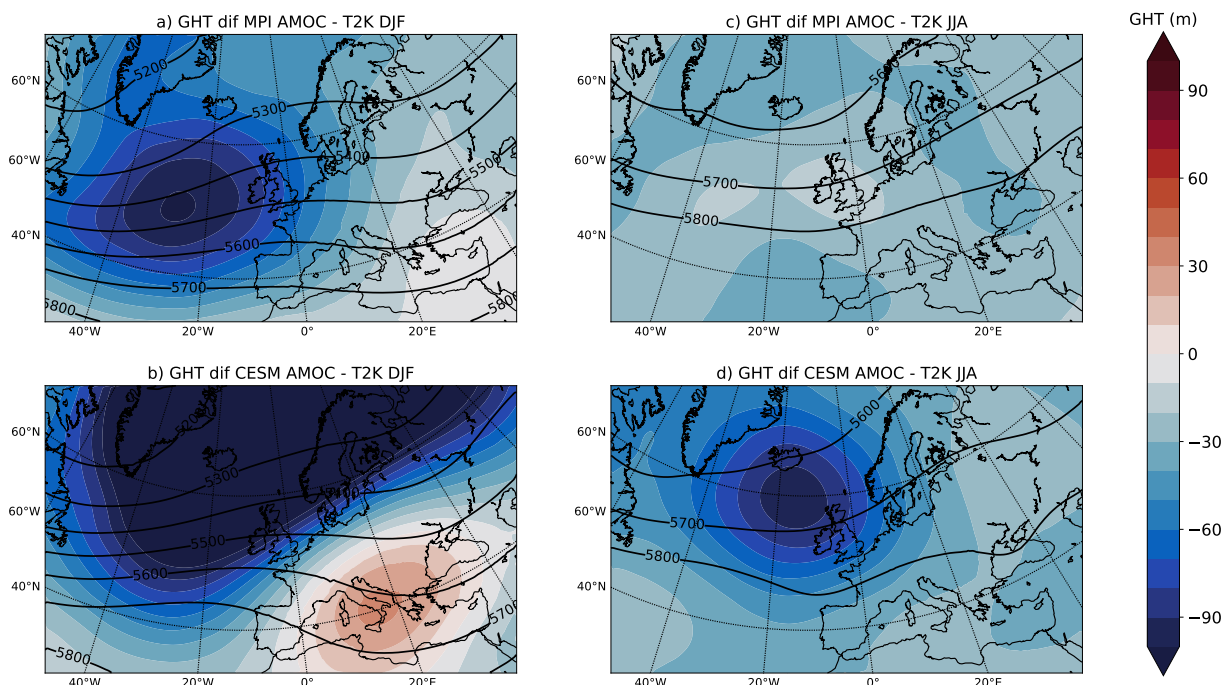


Figure 13. Difference in a), b) DJF and c), d) mean geopotential height at 500 hPa (shading) between the stable_T2K and the piControl simulations for a), c) the MPI-driven and b), d) the CESM-driven WRF downscaling. Black contours represent the seasonal mean of 500-hPa geopotential height in piControl.

represents the transition from pre-industrial conditions towards an AMOC strength comparable to present-day observations (McCarthy et al., 2015).

The differing responses obtained here are consistent with previous studies showing substantial inter-model variability in the North Atlantic jet modification to global warming (Blackport and Fyfe, 2022; Peings et al., 2018). These studies also highlight the difficulty that current climate models have in reproducing the observed trends in the North Atlantic jet. All these results suggest that differences in the simulated AMOC response to warming may contribute to the spread in projected changes in the North Atlantic jet through their influence on North Atlantic SSTs and baroclinicity.

The role of the AMOC becomes even more evident in the hosing experiments, where both models are forced towards a similarly weak overturning circulation despite their different initial states after the global mean temperature ramp-up. Consequently, the atmospheric response in this scenario also depends strongly on the background state simulated by each ESM. Although both models reach a similarly weak AMOC following the hosing experiment, they start from different AMOC strengths under

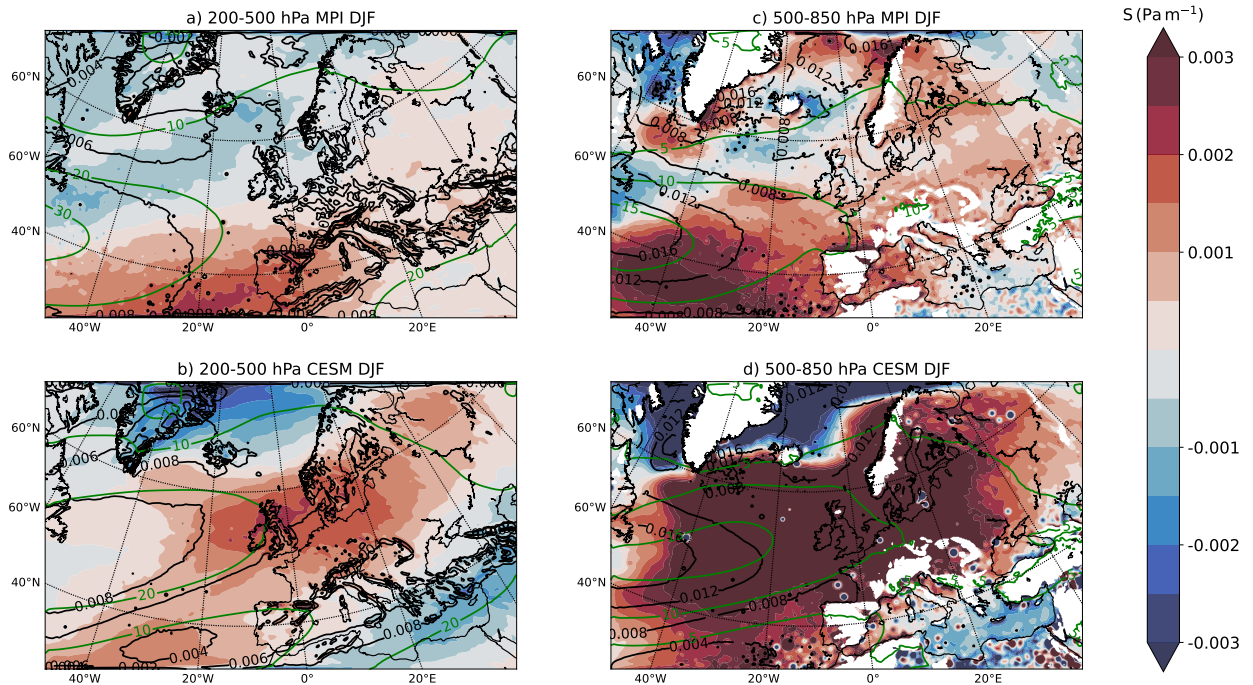


Figure 14. Difference in mean DJF isentropic slope (shading) averaged between a), b) 200 and 500 hPa and c), d) 500 and 850 hPa between the stable_T2K_AMOC and the stable_T2K simulations for a), c) the MPI-driven and b), d) the CESM-driven WRF downscaling. The black contours represent the seasonal mean of the isentropic slope averaged over the corresponding pressure levels, while the green contours show the mean zonal wind speed at 250 hPa in the respective piControl simulation. Areas with orography higher than 500 m are masked in panels c) and d).

the stable_T2K climate. In the CESM simulation, the collapse represents a transition from an AMOC strength comparable to present-day conditions to a substantially weakened state. This produces pronounced cooling of the Northern Hemisphere, particularly at high latitudes, strengthening the meridional temperature gradients and intensifying the North Atlantic jet. This behaviour is consistent with the response reported in CMIP models following a strong AMOC decline (Meccia et al., 2024; Orbe et al., 2023).

By contrast, the MPI simulation begins from a weaker AMOC under stable_T2K and therefore exhibits a smaller thermodynamic response to the hosing experiment. The winter circulation response is characterised by a pronounced equatorward displacement of the jet. In both models, the circulation response is considerably stronger during winter than summer, consistent with the larger cooling and stronger meridional temperature gradients during the cold season.

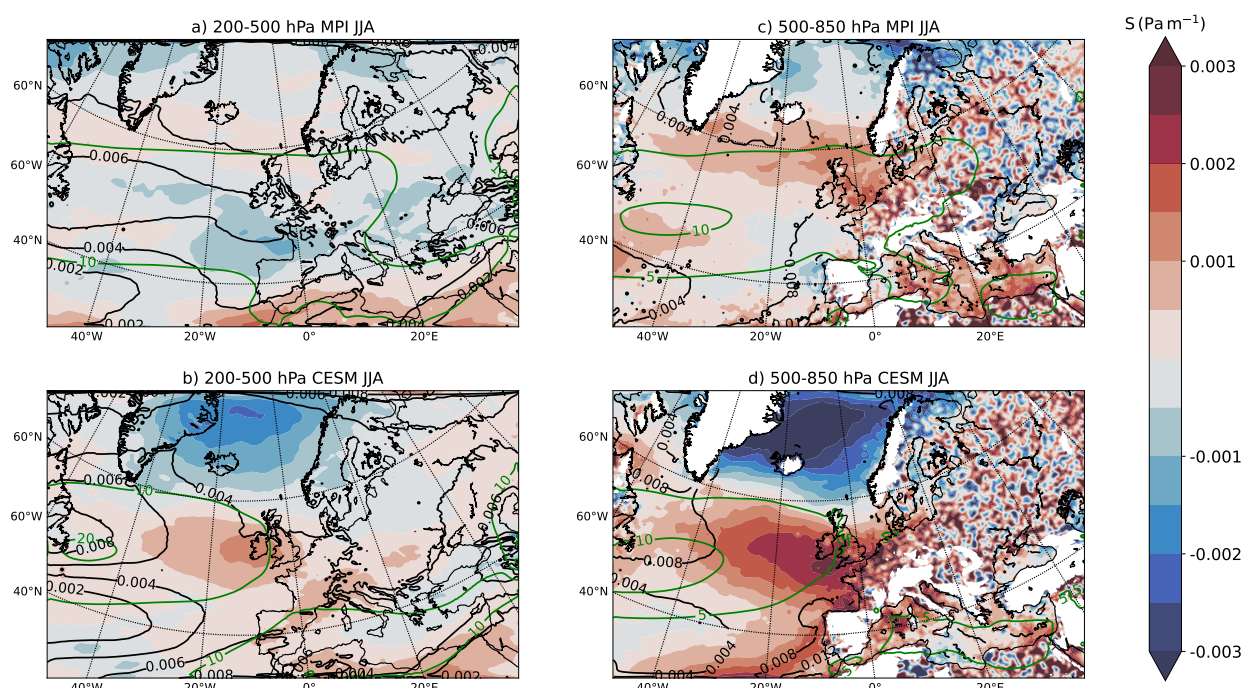


Figure 15. As in Fig. 14 for summer (JJA).

The regional simulations broadly reproduce the large-scale circulation changes of their driving ESMs under both global warming and AMOC collapse, indicating that the primary characteristics of the atmospheric response are inherited from the large-scale forcing. Nevertheless, important regional differences emerge, particularly over the central part of the domain, where the influence of the lateral boundary conditions is weaker. These differences highlight the added value of dynamical downscaling in resolving regional-scale circulation features while also illustrating that regional simulations inevitably inherit part of the systematic biases of their driving ESMs (Zhang et al., 2024).

The differences between the two ESMs further emphasise the importance of model uncertainty in projections of future North Atlantic jet stream. Previous studies have identified inter-model differences as the dominant source of uncertainty in the AMOC response to increasing greenhouse gas concentrations (Reintges et al., 2017; Baker et al., 2023). Although our analysis is based on only two ESMs, the regional dynamical downscaling shows that differences in the simulated AMOC response are largely preserved at the regional scale, resulting in markedly different baroclinicity patterns and North Atlantic jet changes. At the same time, the downscaling reveals regional-scale circulation differences that are not fully captured by the driving ESMs, highlighting its added value for investigating regional climate responses. Together, these findings emphasise the importance



of considering uncertainty in the simulated AMOC response when interpreting regional projections of future North Atlantic
310 atmospheric jet stream.

5 Conclusions

This study investigated the response of the North Atlantic jet stream to global warming and an additional AMOC collapse using regional dynamical downscaling driven by two ESMs. Specifically, we examined (i) the added value of regional dynamical downscaling relative to the driving ESMs, (ii) the physical mechanisms linking global warming and AMOC collapse to changes
315 in the jet stream, and (iii) the robustness of these responses across different driving models.

The regional simulations broadly preserve the large-scale circulation changes simulated by the driving ESMs, including shifts in the North Atlantic jet and changes in its intensity. At the same time, the dynamical downscaling refines the spatial structure of the simulated jet response, particularly over the interior of the domain, where the influence of the lateral boundary conditions is weaker. These differences are especially evident during summer, when the jet is weaker.

320 The response of the North Atlantic jet depends strongly on the evolution of the AMOC. Under global warming, the two ESMs simulate different AMOC weakening, leading to contrasting SST patterns, meridional temperature gradients and baroclinicity changes. Consequently, the MPI-driven simulations exhibit an equatorward displacement of the winter jet associated with stronger Arctic amplification and a more pronounced North Atlantic warming hole, whereas the CESM-driven simulations show a poleward jet shift. The atmospheric circulation response again depends on the background AMOC state in the AMOC
325 collapse scenario. The CESM-driven simulations display strong high-latitude cooling and a marked jet intensification, whereas the MPI-driven simulations retain an equatorward-displaced jet despite a weaker thermodynamic response.

The contrasting responses obtained with the two ESMs demonstrate that the simulated atmospheric response is sensitive to the representation of the AMOC. Although the analysis is limited to two driving models, it shows that differences in the AMOC response propagate through the regional dynamical downscaling, producing markedly different baroclinicity changes
330 and jet responses. Extending this framework to a larger ensemble of ESMs would enable a more comprehensive assessment of the uncertainty associated with future projections of the North Atlantic jet stream.

This study extends previous investigations of the atmospheric impacts of AMOC weakening and collapse by applying regional dynamical downscaling to AMOC tipping experiments. The regional simulations show that the large-scale circulation response of the driving ESMs is broadly preserved, while also revealing regional modifications to the North Atlantic jet that
335 are not fully represented in the coarse-resolution models. These findings demonstrate the added value of regional dynamical downscaling for assessing the regional atmospheric impacts of AMOC tipping and provide a basis for future multi-model studies of regional climate responses.



Author contributions. AH ran the WRF downscaling simulations, analysed the results and drafted the manuscript. LFC and CRP ran the global simulations. All co-authors contributed to the discussion of the results and revised the manuscript.

340 *Competing interests.* The authors declare no conflict of interest.

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