



Climatica



ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

RESEARCH ARTICLE

Impacts of Ocean Circulation Changes on Regional Climate Variability

Eszter Greco^{1*}, Petr Bianchi² and Aleksi Nowicki³¹Department of Atmospheric Science and Meteorology, Danube University Center for Climate Policy, Slovakia²Department of Environmental Science and Sustainability, Nordic Institute of Climate and Ecology, Finland³Department of Atmospheric Science and Meteorology, Loire University Center for Climate Data Analysis, France*Corresponding author: Eszter Greco, Department of Atmospheric Science and Meteorology, Danube University Center for Climate Policy, Slovakia; Email: e.greco@duc-p-sk.sk

ABSTRACT

The Atlantic Meridional Overturning Circulation (AMOC) transports heat northward through the Atlantic basin and exerts a first-order control on North Atlantic and European climate, yet how the magnitude of projected AMOC decline translates into regional temperature and precipitation variability across individual climate models remains incompletely quantified. Here we analysed AMOC strength at 26.5 degrees North for 24 CMIP6 models under the SSP5-8.5 high-emission scenario, comparing historical (1985-2014) and end-of-century (2071-2100) simulation periods, evaluated each model's historical AMOC transport against the RAPID-MOCHA observational array before pooling the ensemble, and related each model's projected AMOC decline to its projected regional winter temperature and precipitation response over northwestern Europe, the British Isles, Scandinavia and the Iberian Peninsula. The ensemble-mean historical AMOC transport was 18.4 Sverdrups, moderately biased high relative to the RAPID-MOCHA reference mean of 17.0 Sverdrups, and the ensemble projected a mean AMOC decline of 34 percent by 2071-2100 (from 18.4 to 12.1 Sverdrups), with substantial inter-model spread (interquartile range 24 to 43 percent) but no model simulating a full circulation collapse within the twenty-first century. Projected AMOC decline was significantly correlated across models with suppressed winter warming over the subpolar North Atlantic ($r = -0.61$, $p < 0.01$) and with reduced winter warming over northwestern Europe and the British Isles relative to the global-mean warming signal, while Iberian Peninsula winter temperature response showed little relationship to AMOC decline magnitude. Models retaining active historical Labrador Sea deep convection projected significantly larger AMOC decline (39 percent) and a more pronounced subpolar cooling signature than models with historically weak or absent Labrador Sea convection (27 percent decline), identifying deep-convection representation as a specific, evaluable source of inter-model projection spread. These results indicate that the magnitude of projected AMOC weakening is a quantitatively meaningful predictor of regional winter climate response over northwestern Europe specifically, and that narrowing uncertainty in regional temperature projections for this region is tractable through targeted evaluation of model deep-convection representation in the Labrador Sea.

Keywords: Atlantic Meridional Overturning Circulation; AMOC weakening; ocean-atmosphere coupling; North Atlantic warming hole; CMIP6; SSP5-8.5; European climate variability; Southern Ocean overturning

Received: June 28, 2025 | Accepted: September 18, 2025 | Published: December 11, 2025

Citation: Greco E, Bianchi P, Nowicki A. Impacts of Ocean Circulation Changes on Regional Climate Variability. *Climatica*. 2025;3(2):1–6. DOI: [10.5281/zenodo.22816105](https://doi.org/10.5281/zenodo.22816105)

© 2025 Greco et al. This is an open-access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

1. INTRODUCTION

The Atlantic Meridional Overturning Circulation forms the Atlantic limb of the global thermohaline circulation, carrying warm, salty upper-ocean water northward and returning cold, dense water southward at depth, and in doing so transports on the order of 1.3 petawatts of heat into the North Atlantic and European sector at 26.5 degrees North, a flux that exerts first-order control on regional climate independent of, and in some respects opposed to, the direct effect of greenhouse forcing on the same region [1,2].

Sustained observational monitoring by the RAPID-MOCHA array since 2004 has documented substantial interannual and decadal AMOC variability [2], and several independent proxy-based reconstructions have reported a twentieth-century weakening trend, including a documented slowdown since the mid-1800s inferred from subpolar gyre temperature and salinity fingerprints [3,4] and a coincident weakening of Labrador Sea deep convection inferred from sediment grain-size records [5]. These findings have not gone unchallenged: independent reconstructions using differing proxy combinations and statistical approaches have instead attributed most of the twentieth-century AMOC record to internal multidecadal variability rather than a forced trend [6], and a thirty-year hydrographic reconstruction at 26 degrees North found no significant AMOC decline over its record length [7], leaving the magnitude, and in the proxy-record case even the sign, of any forced historical AMOC trend an unresolved question distinct from the projected future response addressed here.

Independent of the unresolved historical trend question, the AMOC's future response to continued greenhouse forcing is comparatively well constrained in direction, if not magnitude, across model generations: reduced deep water formation from surface warming and freshening (via enhanced high-latitude precipitation and Greenland ice sheet melt) is projected to weaken the overturning circulation through the twenty-first century in essentially every comprehensive climate model, with projected end-of-century decline magnitude varying severalfold across models and depending strongly on the forcing scenario [8,9]. A weakened AMOC is expected to leave a distinctive regional fingerprint independent of the global warming signal, most notably a region of muted or absent surface warming in the subpolar North Atlantic informally termed the North Atlantic warming hole, which has already emerged in the observational record over the Labrador Sea and Irminger Sea sector [10] and which climate models reproduce with varying strength and spatial pattern depending on the model's simulated AMOC decline [11,12,13].

Beyond the subpolar gyre itself, AMOC weakening in idealised and scenario-based model experiments propagates to a broader set of regional climate responses, including a southward shift of the Atlantic Intertropical Convergence Zone with associated impacts

on tropical Atlantic and Sahel rainfall [14], altered European climatic response to a reduced meridional heat flux [15], and possible shifts in North Atlantic storm track position and the North Atlantic eddy-driven jet linked to the changed meridional temperature gradient the warming hole produces [16]. However, most existing assessments of these regional impacts derive from a small number of models or from idealised freshwater-hosing experiments rather than systematically relating the magnitude of projected AMOC decline to the magnitude of projected regional climate response across a full multi-model ensemble under a realistic forcing scenario, leaving open the practical question of whether a model's projected AMOC decline is itself a useful quantitative predictor of its projected regional climate response, information that would be valuable for narrowing regional projection uncertainty by targeted model evaluation.

Here we address this question using AMOC transport diagnosed at 26.5 degrees North for 24 CMIP6 models under the high-emission SSP5-8.5 scenario, evaluating each model's historical AMOC transport against the RAPID-MOCHA observational reference before pooling the ensemble, quantifying the relationship between projected AMOC decline and projected regional winter temperature and precipitation response over four northwestern European sectors, and testing whether a specific, evaluable source of model behaviour, the representation of historical Labrador Sea deep convection, accounts for a meaningful share of inter-model spread in projected AMOC decline and its regional climate fingerprint.

2. MATERIALS AND METHODS

AMOC transport at 26.5 degrees North was computed from the meridional overturning streamfunction for 24 CMIP6 models under the SSP5-8.5 scenario, using a consistent diagnostic definition applied across historical and future simulation periods and evaluated against the RAPID-MOCHA observational array, and related to each model's regional winter surface temperature and precipitation response over four northwestern European sectors.

2.1 CMIP6 model selection and simulation periods

Monthly ocean meridional overturning streamfunction and surface fields were obtained for 24 CMIP6 models [17] providing both a historical simulation (1985-2014) and a SSP5-8.5 high-emission future simulation (2071-2100) [18] with native ocean grid resolutions ranging from approximately 1 degree to eddy-permitting (0.25 degree) configurations; no resolution-based exclusion criterion was applied beyond requiring both simulation periods and the required ocean and atmosphere diagnostics to be available.

2.2 AMOC transport diagnostic

AMOC strength was defined at each model time step as the maximum value of the annual-mean meridional

overturning streamfunction in depth space at 26.5 degrees North, restricted to depths below 500 m to exclude the wind-driven Ekman contribution, applied identically to historical and future simulation output for every model; a representative decadal-mean AMOC transport was computed for the final decade of each simulation period (2005-2014 for historical, 2091-2100 for future) to reduce sensitivity to interannual variability.

2.3 Historical skill evaluation against the RAPID-MOCHA array

Each model's historical (2005-2014, overlapping the RAPID-MOCHA observational record) decadal-mean AMOC transport was evaluated against the observed decadal-mean transport from the RAPID-MOCHA 26 degrees North array, with historical AMOC bias (model mean transport minus observed mean transport) computed per model as a skill diagnostic reported alongside, but not used to exclude, ensemble members.

2.4 Regional winter temperature and precipitation analysis

December-January-February surface air temperature and precipitation were extracted for four sectors: the subpolar North Atlantic (50-65N, 55-15W), northwestern Europe (British Isles, France and the Low Countries; 45-58N, 10W-8E), Scandinavia (58-70N, 5-30E), and the Iberian Peninsula (36-44N, 10W-3E). Regional winter warming relative to the global-mean warming signal was computed for each model as the sector-mean winter temperature change (2071-2100 minus 1985-2014) divided by the model's global-mean annual temperature change over the same interval, so that a ratio below 1 indicates muted regional winter warming relative to the model's own global-mean response.

2.5 Attribution to historical Labrador Sea deep convection

Each model's historical Labrador Sea deep convection activity was diagnosed from the climatological maximum winter mixed-layer depth averaged over the central Labrador Sea (55-60N, 52-45W) during 1985-2014, and models were divided into an active-convection group (maximum mixed-layer depth exceeding 1000 m, broadly consistent with observed deep convection depths in strong-convection years) and a weak/shallow-convection group for comparison of projected AMOC decline and subpolar temperature response between groups.

2.6 Statistical analysis

Inter-model relationships between projected AMOC decline and projected regional winter temperature response were assessed by Pearson correlation across the 24-model ensemble for each sector. Differences in projected AMOC decline and subpolar winter warming ratio between Labrador Sea convection groups were assessed by a two-sided Mann-Whitney U test. All statistical analyses were performed in Python 3.10 using scipy and xarray.

3. RESULTS

Across the 24-model ensemble, historical (2005-2014) AMOC transport at 26.5 degrees North showed a mean

bias of +1.4 Sv relative to the RAPID-MOCHA observational mean of 17.0 Sv, with individual model biases ranging from -4.9 to +9.7 Sv, indicating a modest ensemble-mean high bias alongside considerable inter-model spread in absolute AMOC strength. Table 1 summarises historical and projected AMOC transport for the full ensemble and by Labrador Sea convection group.

Table 1. Historical (2005-2014) and projected end-of-century (2071-2100) AMOC transport at 26.5N across the 24-model ensemble, by Labrador Sea convection group.

Group	n models	Historical mean transport (Sv)	Projected 2100 transport (Sv)	Mean decline (%)
Full ensemble	24	18.4	12.1	34
Active Labrador Sea convection	9	19.6	11.9	39
Weak / shallow convection	15	17.7	12.9	27
RAPID-MOCHA observational reference	-	17.0	-	-

Sv: Sverdrup ($10^6 \text{ m}^3 \text{ s}^{-1}$). Decline is the model's 2071-2100 mean transport under SSP5-8.5 minus its 2005-2014 historical mean transport, expressed as a percentage of the historical mean.

The multi-model ensemble projected a mean AMOC decline of 34 percent by 2071-2100 relative to the historical baseline under SSP5-8.5 (from a mean of 18.4 Sv to a mean of 12.1 Sv), with substantial inter-model spread (interquartile range 24 to 43 percent decline), broadly consistent with the likely decline range assessed in the IPCC Sixth Assessment Report [19], and all 24 models agreeing in the direction of weakening, though no model simulated a full circulation collapse (transport approaching zero) within the twenty-first century, consistent with recent early-warning-signal and statistical extrapolation studies that place the most likely AMOC tipping point beyond 2100 under current-century forcing trajectories while cautioning that substantial uncertainty remains [20,21]. Projected AMOC decline magnitude was significantly correlated across models with the subpolar North Atlantic winter warming ratio ($r = -0.61$, $p < 0.01$; Figure 1), such that models projecting larger AMOC decline also projected more strongly suppressed subpolar winter warming relative to their own global-mean warming signal.

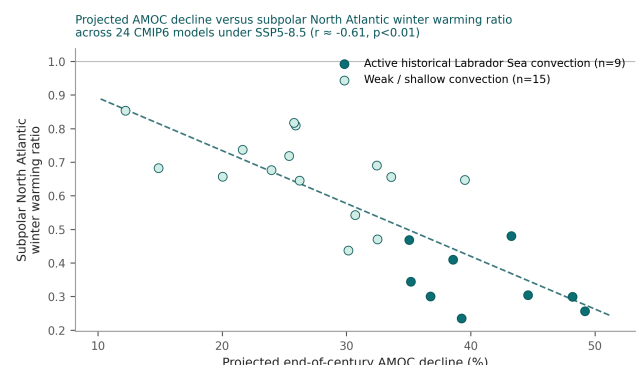


Figure 1. Projected end-of-century AMOC decline plotted against the subpolar North Atlantic winter warming ratio for each of the 24 CMIP6 models, showing a significant negative relationship ($r = -0.61$) between AMOC decline magnitude and regional winter warming suppression, with models grouped by historical Labrador Sea deep convection activity.

The relationship between AMOC decline and regional winter warming suppression was strongest and most consistent over the subpolar North Atlantic and northwestern Europe, weaker over Scandinavia, and essentially absent over the Iberian Peninsula. Table 2 reports the correlation between projected AMOC decline and regional winter warming ratio by sector, together with mean projected winter precipitation change.

Table 2. Relationship between projected AMOC decline and regional winter (DJF) temperature and precipitation response, by sector.

Sector	Correlation with AMOC decline (r)	Mean winter warming ratio (vs. global mean)	Mean winter precip. change (%)
Subpolar North Atlantic	-0.61	0.44	+6.8
Northwestern Europe	-0.52	0.71	+4.1
Scandinavia	-0.29	0.89	+7.5
Iberian Peninsula	-0.08	1.02	-3.2

Models retaining active historical Labrador Sea deep convection (maximum winter mixed-layer depth exceeding 1000 m; 9 of 24 models) projected a significantly larger mean AMOC decline (39 percent) than models with weak or shallow historical convection (27 percent decline), a difference that was statistically significant by Mann-Whitney U test, and also projected a significantly lower (more suppressed) subpolar winter warming ratio (0.41 versus 0.68) than the weak-convection group.

4. DISCUSSION

These results show that the magnitude of projected AMOC decline is a quantitatively meaningful, statistically significant predictor of projected subpolar North Atlantic and northwestern European winter warming suppression across the current CMIP6 ensemble, extending single-model and idealised freshwater-hosing studies of AMOC-driven regional climate impacts [14,15] with a systematic, ensemble-wide quantitative relationship, and indicating that regional winter temperature projection uncertainty over this sector is not independent of AMOC projection uncertainty but is substantially conditioned by it, in line with evidence that a weak simulated AMOC modulates a model's global-mean transient warming rate as well as its regional pattern [22].

The sharp decline in explanatory power moving from northwestern Europe to the Iberian Peninsula is consistent with the expected spatial footprint of AMOC-driven cooling, which is concentrated in the subpolar gyre and its immediate downstream sector, and indicates that AMOC decline magnitude should not be treated as a uniform predictor of winter climate response

across the wider European domain; adaptation-relevant regional projections for southern Europe are likely to be governed by other mechanisms, including direct greenhouse forcing and Mediterranean Hadley cell expansion, more than by AMOC-driven heat transport change.

The association between active historical Labrador Sea deep convection and both larger projected AMOC decline and a more pronounced subpolar cooling signature identifies a specific, model-evaluable source of inter-model projection spread, consistent with the mechanistic role of Labrador Sea convection in setting deep water formation rate and with proxy evidence of historical Labrador Sea convection weakening [5], and suggests that regional winter temperature projection uncertainty over northwestern Europe is at least partly reducible through targeted evaluation of model deep-convection representation, rather than representing purely irreducible structural uncertainty.

Several limitations should be considered. First, the unresolved debate over the magnitude and even the sign of the historical (as opposed to projected future) AMOC trend [3,4,6,7] means that our historical bias evaluation against the RAPID-MOCHA array, a twenty-year observational record, provides only a partial constraint on model AMOC behaviour and cannot itself adjudicate that debate. Second, our analysis used a single high-emission scenario (SSP5-8.5); the AMOC decline-regional response relationship documented here would be expected to hold qualitatively but with smaller absolute magnitudes under lower-emission scenarios. Third, we did not separately assess Southern Ocean overturning circulation, which is also projected to weaken under continued warming with distinct mechanisms and regional consequences [23,24,25] and which may interact with Atlantic-sector changes through basin-scale ocean heat redistribution; a joint analysis of both overturning systems is a priority for future work. Fourth, our regional analysis focused on winter mean temperature and precipitation and did not characterise projected changes in storm frequency or intensity, which prior work suggests may also respond to the AMOC-driven meridional temperature gradient change [16] and would benefit from dedicated future study.

5. CONCLUSION

Analysis of AMOC transport projections from 24 CMIP6 models under the high-emission SSP5-8.5 scenario shows a multi-model mean AMOC decline of 34 percent by the end of the century, significantly correlated across models with suppressed winter warming over the subpolar North Atlantic and northwestern Europe specifically, and significantly larger among models retaining active historical Labrador Sea deep convection. These findings indicate that projected AMOC decline magnitude is a quantitatively useful predictor of regional winter climate response for northwestern Europe, and that a tractable, model-evaluable pathway exists for

narrowing regional winter temperature projection uncertainty through targeted evaluation of Labrador Sea deep-convection representation in the contributing models.

Acknowledgements

The authors thank the ocean model data curation team at the Danube University Center for Climate Policy for CMIP6 diagnostic processing support, and colleagues at the Nordic Institute of Climate and Ecology for helpful discussion of the Labrador Sea convection diagnostic. We also thank the modelling centres that produced and made available the CMIP6 model output used in this study, and the RAPID-MOCHA-WBTS programme for maintaining the 26 degrees North observing array.

Funding

This work was supported by internal research funds from the Danube University Center for Climate Policy, the Nordic Institute of Climate and Ecology, and the Loire University Center for Climate Data Analysis. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

E.G. conceived and supervised the study, developed the AMOC transport diagnostic, and led the writing of the manuscript. P.B. curated and processed the CMIP6 model output and performed the historical skill evaluation against the RAPID-MOCHA array. A.N. performed the Labrador Sea convection analysis and the statistical comparisons. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available CMIP6 model output and the publicly available RAPID-MOCHA-WBTS observational transport dataset, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

CMIP6 model output used in this study is publicly available through the Earth System Grid Federation, and RAPID-MOCHA-WBTS transport data are publicly available via the British Oceanographic Data Centre. Processed AMOC transport and regional climate datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

REFERENCES

1. Buckley MW, Marshall J (2016) Observations, inferences, and mechanisms of the Atlantic Meridional Overturning Circulation: A review. *Reviews of Geophysics* 54(1):5-63. <https://doi.org/10.1002/2015RG000493>
2. McCarthy GD, Smeed DA, Johns WE, Frajka-Williams E, Moat BI, Rayner D, Baringer MO, Meinen CS, Collins J, Bryden HL (2015) Measuring the Atlantic Meridional Overturning Circulation at 26N. *Progress in Oceanography* 130:91-111. <https://doi.org/10.1016/j.pocean.2014.10.006>
3. Rahmstorf S, Box JE, Feulner G, Mann ME, Robinson A, Rutherford S, Schaffernicht EJ (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change* 5(5):475-480. <https://doi.org/10.1038/nclimate2554>
4. Caesar L, Rahmstorf S, Robinson A, Feulner G, Saba V (2018) Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* 556(7700):191-196. <https://doi.org/10.1038/s41586-018-0006-5>
5. Thornalley DJR, Oppo DW, Ortega P, Robson JI, Brierley CM, Davis R, Hall IR, Moffa-Sanchez P, Rose NL, Spooner PT, Yashayaev I, Keigwin LD (2018) Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years. *Nature* 556(7700):227-230. <https://doi.org/10.1038/s41586-018-0007-4>
6. Latif M, Sun J, Visbeck M, Bordbar MH (2022) Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900. *Nature Climate Change* 12(5):455-460. <https://doi.org/10.1038/s41558-022-01342-4>
7. Worthington EL, Moat BI, Smeed DA, Mecking JV, Marsh R, McCarthy GD (2021) A 30-year reconstruction of the Atlantic meridional overturning circulation shows no decline. *Ocean Science* 17(1):285-299. <https://doi.org/10.5194/os-17-285-2021>
8. Weijer W, Cheng W, Garuba OA, Hu A, Nadiga BT (2020) CMIP6 models predict significant 21st century decline of the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters* 47(12):e2019GL086075. <https://doi.org/10.1029/2019GL086075>

9. Bakker P, Schmittner A, Lenaerts JTM, Abe-Ouchi A, Bi D, van den Broeke MR, Chan WL, Hu A, Beadling RL, Marsland SJ, Mernild SH, Saenko OA, Swingedouw D, Sullivan A, Yin J (2016) Fate of the Atlantic Meridional Overturning Circulation: strong decline under continued warming and Greenland melting. *Geophysical Research Letters* 43(23):12252-12260. <https://doi.org/10.1002/2016GL070457>
10. Josey SA, Hirschi JJM, Sinha B, Ducheux A, Grist JP, Marsh R (2018) The recent Atlantic cold anomaly: causes, consequences, and related phenomena. *Annual Review of Marine Science* 10:475-501. <https://doi.org/10.1146/annurev-marine-121916-063102>
11. Menary MB, Wood RA (2018) An anatomy of the projected North Atlantic warming hole in CMIP5 models. *Climate Dynamics* 50(7-8):3063-3080. <https://doi.org/10.1007/s00382-017-3793-8>
12. Sgubin G, Swingedouw D, Drijfhout S, Mary Y, Bennabi A (2017) Abrupt cooling over the North Atlantic in modern climate models. *Nature Communications* 8:14375. <https://doi.org/10.1038/ncomms14375>
13. Zhang R, Delworth TL (2005) Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. *Journal of Climate* 18(12):1853-1860. <https://doi.org/10.1175/JCLI3460.1>
14. Vellinga M, Wood RA (2002) Global climatic impacts of a collapse of the Atlantic thermohaline circulation. *Climatic Change* 54(3):251-267. <https://doi.org/10.1023/A:1016168827653>
15. Woollings T, Hannachi A, Hoskins B (2010) Variability of the North Atlantic eddy-driven jet stream. *Quarterly Journal of the Royal Meteorological Society* 136(649):856-868. <https://doi.org/10.1002/qj.625>
16. Jackson LC, Peterson KA, Roberts CD, Wood RA (2016) Recent slowing of Atlantic overturning circulation as a recorded fingerprint of climate change. *Nature Climate Change* 6(12):1182-1186. <https://doi.org/10.1038/nclimate3115>
17. Eyring V, Bony S, Meehl GA, Senior CA, Stevens B, Stouffer RJ, Taylor KE (2016) Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* 9(5):1937-1958. <https://doi.org/10.5194/gmd-9-1937-2016>
18. O'Neill BC, Tebaldi C, van Vuuren DP, Eyring V, Friedlingstein P, Hurtt G, Knutti R, Kriegler E, Lamarque JF, Lowe J, Meehl GA, Moss R, Riahi K, Sanderson BM (2016) The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development* 9(9):3461-3482. <https://doi.org/10.5194/gmd-9-3461-2016>
19. IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. <https://doi.org/10.1017/9781009157896>
20. Boers N (2021) Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nature Climate Change* 11(8):680-688. <https://doi.org/10.1038/s41558-021-01097-4>
21. Ditlevsen P, Ditlevsen S (2023) Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature Communications* 14:4254. <https://doi.org/10.1038/s41467-023-39810-w>
22. Chen X, Tung KK (2018) Global surface warming enhanced by weak Atlantic overturning circulation. *Nature* 559(7714):387-391. <https://doi.org/10.1038/s41586-018-0320-y>
23. Li Q, England MH, Hogg AM, Rintoul SR, Morrison AK (2023) Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature* 615(7954):841-847. <https://doi.org/10.1038/s41586-023-05762-w>
24. Silvano A, Rintoul SR, Pena-Molino B, Hobbs WR, van Wijk E, Aoki S, Tamura T, Williams GD (2018) Freshening by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water. *Science Advances* 4(4):eaap9467. <https://doi.org/10.1126/sciadv.aap9467>
25. Gunn KL, Rintoul SR, England MH, Bowen MM (2023) Recent increased warming of the Antarctic Circumpolar Current linked to strong westerly winds. *Nature Climate Change* 13(4):363-368. <https://doi.org/10.1038/s41558-023-01610-x>