

Western North Atlantic Sea level reveals enhanced future AMOC Weakening

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Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is a key regulator of global climate and a major driver of regional sea-level variability in the North Atlantic. However, its long-term evolution remains uncertain, with climate models projecting a weakening under greenhouse-gas forcing but exhibiting substantial inter-model spread. Previous attempts to constrain AMOC variability have relied on indicators, such as surface temperature, that may conflate multiple physical processes. Here, we show that coastal dynamic sea level provides a direct and robust proxy for large-scale overturning variability. We introduce a sea-level gradient index, based on the difference between southern (29–39°N, 75–55°W) and northern (43–53°N, 58–38°W) regions, supported by modelled relationships derived from CMIP6, and observed relationships from reanalysis and satellite observations. This index captures AMOC-driven variability across interannual to multidecadal timescales and enables reconstruction of a longer-term AMOC record from tide-gauge data. Climate models that better reproduce the observed relationship between coastal sea level and AMOC variability show improved agreement with the inferred historical evolution. Finally, these results show observationally constrained CMIP6 models having a 53.4% weakening under a high emissions SSP5-8.5 scenario and a 36.0% weakening under a low emissions SSP1-2.6 scenario by 2100, a larger weakening than the 45.3% and 29.0%, respectively, reported by IPCC, reemphasizing the importance of a low emission future to avoid more extreme AMOC futures.

Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is a central component of the climate system, regulating the redistribution of heat, freshwater, and carbon across the Atlantic basin and exerting a strong influence on regional and global climate variability^{1,2}. Variations in AMOC strength have been linked to changes in sea surface temperatures, precipitation patterns, and extreme weather, particularly in the North Atlantic region^{3–5}. Of particular importance is the role of the AMOC in shaping dynamic sea level (DSL), as changes in ocean circulation alter the distribution of mass and density, leading to regional sea-level responses^{6,7}. Along the western boundary of the North Atlantic, AMOC variability has been associated with pronounced coastal sea-level fluctuations north of Cape Hatteras on the U.S. East Coast^{8,9} with important implications for these densely populated coastal regions.

Climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) consistently project a weakening of the AMOC under greenhouse gas forcing, but the magnitude, timing, and regional impacts of this decline vary widely across models^{7, 9, 10}. This inter-model spread arises from differences in the representation of key processes, including deep-water formation, ocean stratification, and boundary-current dynamics¹¹ and limits confidence in projections of AMOC-related climate change. Reducing this uncertainty is therefore a major challenge in climate science^{12, 13, 14}.

One promising approach to addressing this challenge is the use of emergent constraints, which exploit relationships between observed present-day variability and long-term model response. Previous studies have applied emergent constraint frameworks to AMOC variability using surface temperature patterns

and large-scale climate indices^{12,13,15,16}. However, these approaches are often indirect and may conflate multiple physical processes. In contrast, dynamic sea level (DSL) provides a more direct measure of ocean circulation changes, as it reflects the integrated response of ocean density and mass distribution to variations in large-scale transport^{8,9}.

Here, we investigate whether the relationship between AMOC strength and DSL can serve as a physically grounded and observationally constrained metric for evaluating climate models. Figure 1a shows spatial correlations between the Atlantic Meridional Overturning Circulation and dynamic sea level anomalies derived from observations. This relationship is characterized by positive correlations in the subtropical gyre and negative correlations in the subpolar North Atlantic. Using a combination of satellite altimetry, tide-gauge records, and ocean reanalysis products, we construct a sea-level index that captures this relationship. We define the DSL gradient index as the difference averaged over the southern (29–39°N, 75–55°W) and northern (43–53°N, 58–38°W) of the western North Atlantic and evaluate CMIP6 models based on their ability to reproduce the observed AMOC–DSL relationship.

Based on each model's ability to reproduce the observed spatial AMOC–DSL relationship, we applied an observational constraint that assigns higher weights to models exhibiting greater agreement with observations (Methods). Models exceeding a predefined observational-consistency threshold were classified as the constrained ensemble, while the remaining models are referred to hereafter as the unconstrained ensemble. Figure 1b–d shows the constrained ensemble, the unconstrained ensemble, and the Full CMIP6 ensemble (the complete set of 20 CMIP6 models is shown in Supplementary Fig. 1). The constrained ensemble reproduces the observed spatial correlation structure more faithfully than the unconstrained ensemble and the Full CMIP6 ensemble, particularly along the U.S. East Coast, where AMOC-related dynamic sea-level variability is strongest.

Relationship between AMOC and Dynamic Sea Level (DSL) index

Here, we further examine the relationship between AMOC strength and the DSL gradient index in observations and CMIP6 ensemble simulations (Fig. 2). Most CMIP6 models exhibit positive synchronous variability between AMOC strength and the DSL gradient index (Supplementary Fig. 2). The multi-model ensemble mean indicates a pronounced AMOC weakening over recent decades, with persistent negative anomalies emerging since the early 1990s and an average decline of approximately 0.45 Sv decade⁻¹. Although most individual models exhibit a statistically significant weakening, some models show only modest changes or slight strengthening, reflecting inter-model differences in ocean–atmosphere coupling and internal variability. Previous studies have suggested that part of the simulated late twentieth-century AMOC weakening in some CMIP6 models may be associated with an enhanced response to anthropogenic aerosol forcing, potentially contributing to stronger declines in multi-model means^{17,18}. Despite this spread, the ensemble consistently indicates a weakening AMOC, consistent with observational evidence and previous modelling studies^{19,20}.

Comparison between observed (AMOC from ocean reanalysis and DSL from satellite altimetry) and the CMIP6 ensemble mean over 1993–2014 reveals strong agreement in both AMOC strength and DSL gradient index (DSL). The CMIP6 ensemble mean closely reproduces the observed variability in both AMOC strength ($r = 0.90$) and the DSL gradient index ($r = 0.89$), indicating strong observational consistency.

Validation of the Tide gauge (TG) derived AMOC using Satellite

Direct observations of the Atlantic Meridional Overturning Circulation (AMOC) remain limited, spanning only the satellite era (since 2004). Tide gauge (TG) records measure coastal sea level and extend back to the late 19th century. Given the relationship between offshore sea level and AMOC reiterated in the previous section, these coastal sea level records offer potential for reconstructing past AMOC variability and for validating model simulations. However, TG measurements are influenced by vertical land motion and other local processes, which can introduce biases in long-term trends. To reduce the influence of local vertical land motion and other site-specific effects, each tide-gauge record was adjusted using the difference between the linear trends derived from satellite altimetry and the corresponding tide-gauge record over their common period (1993–2019), following approaches that combine satellite altimetry and tide-gauge observations to isolate large-scale oceanic sea-level variability from local coastal influences and vertical land motion¹⁹. This approach helps minimise local trend biases while preserving the temporal variability associated with AMOC changes.

Here, we compare the satellite-derived sea surface height (SSH) gradients with the corresponding tide-gauge (TG) gradients derived from Fernandina Beach, Florida, and Sandy Hook, New Jersey (Fig. 1a), to assess the suitability of TG records as a proxy for AMOC-related variability. Regional variability in the southern (29–39°N, 75–55°W) and northern (43–53°N, 58–38°W) western North Atlantic was compared with nearby tide-gauge records to identify stations that best represent the large-scale coastal sea-level signal. Fernandina Beach and Sandy Hook exhibited the strongest correlation with the southern and northern SSH regions, respectively (Supplementary Fig. 3), and were therefore used to construct the coastal sea-level gradient index (TG gradient index) as shown in Supplementary 4. Figure 3 shows that the adjusted TG gradient index closely follows the variability in satellite SSH over the overlapping period (1993–2019), yielding a statistically significant positive correlation ($r = 0.66$, $p < 0.001$). This agreement indicates that the trend-adjustment procedure effectively reduces non-oceanographic influences while preserving the large-scale coastal sea-level variability associated with AMOC changes.

Overall, the results demonstrate that bias-corrected TG records reproduce a substantial fraction of the interannual variability observed in satellite SSH. This supports the use of the corrected TG-derived sea-level gradient as a proxy for reconstructing AMOC variability prior to the satellite era.

Evaluation of CMIP6 AMOC against TG-derived estimates

Figure 4 compares the tide-gauge (TG)–derived AMOC estimate with both constrained and unconstrained CMIP6 AMOC estimates for the period 1950–2014. The constrained CMIP6 ensemble reproduces the temporal evolution of the TG-based AMOC index more faithfully than the unconstrained ensemble, with the differences between the two becoming particularly pronounced during the late twentieth-century decline.

During 1950–1990, the TG-derived AMOC index exhibits a weak positive trend of $0.337 \text{ decade}^{-1}$. The constrained ensemble closely reproduces this behaviour, with a nearly identical trend of $0.329 \text{ decade}^{-1}$ and a statistically significant correlation with the TG reconstruction ($r = 0.56$, $p = 0.0001$). In comparison, the unconstrained ensemble shows a weaker positive trend of $0.215 \text{ decade}^{-1}$ and a much lower, non-significant correlation with the TG-derived estimate ($r = 0.12$, $p = 0.4437$), suggesting limited skill in reproducing the observed temporal evolution. The root mean square error (RMSE) values show a more nuanced behaviour: although the unconstrained ensemble has a slightly lower RMSE than the constrained ensemble during this period (0.820 versus 0.901), its substantially weaker and non-significant correlation indicates poorer representation of the observed variability and phase evolution.

During 1990–2014, the TG-derived AMOC index transitions into a pronounced weakening phase, with a trend of $-0.673 \text{ decade}^{-1}$. The constrained ensemble captures this decline well, reproducing both the sign and magnitude of the weakening trend ($-0.663 \text{ decade}^{-1}$) and exhibiting a statistically significant correlation with the TG reconstruction ($r = 0.67$, $p = 0.0004$). In contrast, the unconstrained ensemble substantially underestimates the weakening trend ($-0.132 \text{ decade}^{-1}$) and shows weak, non-significant correspondence with the TG-derived variability ($r = 0.22$, $p = 0.2941$). Performance differences are also evident in the RMSE metric, with the constrained ensemble showing substantially smaller errors (RMSE = 0.577) than the unconstrained ensemble (RMSE = 0.908), indicating improved representation of the recent AMOC decline.

Overall, these results show that the observationally constrained CMIP6 ensemble better captures the TG-derived AMOC evolution than the unconstrained models, particularly during the post-1990 weakening period. The constrained ensemble exhibits stronger and statistically significant correlations, more realistic trend magnitudes, and lower errors during the recent decline. Nevertheless, some residual discrepancies remain, and the full-period correlations remain modest, indicating that even observation-consistent models do not fully reproduce the amplitude and complexity of observed multidecadal AMOC variability.

Historical evolution and future projections of AMOC

Table 1

Projected AMOC weakening (2091–2100 relative to 1950–2000). Values show the ensemble-mean percentage AMOC weakening under SSP5-8.5 and SSP1-2.6. Uncertainties represent ± 1 standard deviation across models and quantify inter-model spread. The constrained ensemble ($n = 16$) consists of models selected using the observational AMOC–dynamic sea-level constraint; the full CMIP6 ensemble comprises all 20 models.

Projected AMOC weakening (2091–2100 relative to 1950–2000)		
Ensemble Group	SSP585 (%)	SSP126 (%)
Constrained ensemble ($n = 16$)	53.4 ± 16.0	36.0 ± 20.9
Full CMIP6 ensemble ($n = 20$)	45.3 ± 20.3	29.0 ± 22.0

Figure 5 illustrates the evolution of AMOC anomalies at 26.5°N from 1950 to 2100 for the constrained and Full CMIP6 ensemble under the SSP585 and SSP126 emission scenarios. The constrained ensemble reproduces the historical tide-gauge-derived AMOC variability reasonably well, exhibiting a significant correlation with the reconstructed AMOC index over 1950–2014 ($r = 0.54$, $p < 0.001$). Lag-correlation analysis further indicates that CMIP6 AMOC variability leads the tide-gauge reconstruction by approximately two years, suggesting that large-scale overturning changes precede the associated coastal sea-level response.

Future projections indicate a substantial weakening of the AMOC during the twenty-first century under both forcing scenarios, with the magnitude of decline strongly dependent on greenhouse-gas emissions. Under the high-emission SSP585 scenario, the constrained ensemble projects a mean AMOC anomaly of -5.42 Sv during 2015–2100, accompanied by enhanced inter-model variability ($\sigma = 2.57$ Sv) and a pronounced weakening trend of -1.02 Sv decade $^{-1}$. The Full CMIP6 ensemble also projects a substantial decline, although with a smaller mean anomaly (-4.23 Sv), reduced variability ($\sigma = 2.13$ Sv), and a weaker trend (-0.85 Sv decade $^{-1}$). Relative to the 1950–2000 baseline, the constrained and Full CMIP6 ensemble project mean AMOC weakening of $53.4 \pm 16.0\%$ and $45.3 \pm 20.3\%$, respectively, by 2091–2100 (Table 1).

Under the lower-emission SSP126 scenario, AMOC weakening is moderated but remains substantial. The constrained ensemble projects a mean anomaly of -4.70 Sv, variability of 1.51 Sv, and a weakening trend of -0.58 Sv decade $^{-1}$, while the Full CMIP6 ensemble exhibits a mean anomaly of -3.55 Sv, variability of 1.17 Sv, and a trend of -0.44 Sv decade $^{-1}$. By the end of the century, the corresponding reductions relative to the 1950–2000 baseline reach $36.0 \pm 20.9\%$ and $29.0 \pm 22.0\%$ for the constrained and Full CMIP6 ensemble, respectively.

Overall, the results indicate that AMOC weakening is a robust feature across CMIP6 projections, although its magnitude is strongly dependent on future emissions. The constrained ensembles consistently project larger declines, greater variability, and steeper weakening trends than their Full CMIP6 ensemble counterparts, suggesting that observational constraints preferentially select models

with a stronger sensitivity of AMOC to anthropogenic forcing. The substantially larger weakening under SSP585 relative to SSP126 highlights the importance of future greenhouse-gas mitigation in limiting reductions in Atlantic overturning circulation during the twenty-first century.

Discussion

Considerable inter-model spread remains in simulations of the Atlantic Meridional Overturning Circulation (AMOC) and its associated dynamic sea-level (DSL) response^{9, 10}. This uncertainty limits confidence in projections of future North Atlantic climate variability and regional sea-level change. In this study, we applied emergent constraints, which link observed present-day variability to long-term model responses. Previous studies have applied this framework to AMOC variability using surface temperature patterns and large-scale climate indices^{12, 13, 15, 16}. However, these approaches are often indirect and may combine multiple physical processes. In contrast, dynamic sea level provides a more direct indicator of changes in ocean circulation by reflecting variations in ocean density, mass distribution, and large-scale transport^{8,9}.

Using satellite altimetry, ocean reanalyses, tide-gauge observations, and CMIP6 historical simulations, we defined a sea-level gradient index (DSL Index) representing the difference between northern and southern western North Atlantic sea-level anomalies. Both observations and CMIP6 models reveal a coherent AMOC–DSL relationship characterized by positive correlations in the subtropical gyre and negative correlations in the subpolar North Atlantic, supporting the physical basis of using coastal dynamic sea level as a proxy for AMOC variability.

The observationally constrained ensemble, identified using a Gaussian weighting framework based on each model's ability to reproduce the observed AMOC–dynamic sea-level relationship, exhibits substantially improved agreement with the tide-gauge-derived AMOC reconstruction relative to the unconstrained ensemble. During 1950–2014, the constrained ensemble captures the observed multidecadal variability more faithfully and shows a statistically significant correlation with the reconstructed AMOC index, whereas the unconstrained ensemble display little skill. Lead–lag analysis further suggests that the highest agreement occurs when AMOC variability leads the tide-gauge reconstruction by two (2) years, consistent with previous studies linking AMOC changes to western boundary dynamic sea-level variability through geostrophic and large-scale ocean dynamical adjustment processes^{8,19}.

The constrained ensemble also reproduces the recent weakening phase of the AMOC more realistically than the unconstrained ensemble. During 1990–2014, both the reconstructed and simulated AMOC indices exhibit pronounced negative trends, with stronger temporal agreement and reduced RMSE relative to earlier decades. These results suggest that models capable of reproducing the observed AMOC–DSL relationship are also more successful at capturing observed multidecadal AMOC variability, supporting the use of the AMOC–DSL relationship as a physically meaningful model evaluation metric.

Our reconstruction also contributes to the ongoing debate regarding the historical evolution of the AMOC and the ability of climate models to reproduce observed changes. Several observational studies have suggested that the AMOC has undergone a substantial weakening since the mid-twentieth century. For example, Caesar et al.²⁰ identified a characteristic sea-surface temperature fingerprint consistent with a long-term AMOC decline, while Caesar et al.²¹ subsequently argued that the contemporary AMOC may be at its weakest state of the last millennium. These studies have raised concerns regarding the extent to which CMIP6 models capture the magnitude and timing of observed AMOC variability.

The tide-gauge-based reconstruction presented here likewise indicates a pronounced weakening of the AMOC during recent decades, thereby providing independent support for the emerging observational evidence of a declining overturning circulation. However, unlike some reconstructions that imply a more gradual long-term weakening beginning in the mid-twentieth century, the decline in our reconstruction is concentrated primarily after 1990. This difference suggests that estimates of historical AMOC evolution remain sensitive to the observational fingerprint used for reconstruction and may reflect differing sensitivities to forced and internal variability. Nevertheless, both approaches indicate a substantial recent AMOC weakening and therefore support the broader conclusion that the contemporary AMOC is weaker than during much of the twentieth century.

Our findings are particularly relevant to the concerns raised by McCarthy and Caesar²² regarding the credibility of future AMOC projections from models that fail to reproduce historical AMOC evolution. The observationally constrained ensemble identified here not only reproduces the observed AMOC–dynamic sea-level relationship but also exhibits substantially improved agreement with the reconstructed AMOC variability during the historical period. This result suggests that reproducing observed circulation fingerprints provides an important test of model fidelity and supports the argument that historical performance should be considered when assessing confidence in future AMOC projections. More broadly, the improved performance of the constrained ensemble implies that physically based sea-level fingerprints can help identify models that more realistically represent the mechanisms governing AMOC variability and change.

Future projections indicate substantial AMOC weakening during the twenty-first century under both SSP585 and SSP126 scenarios, although the magnitude of decline strongly depends on emission pathway and model selection. The stronger AMOC weakening projected by the constrained ensemble is consistent with recent studies suggesting that observational constraints tend to favour larger future AMOC declines than the CMIP6 multi-model mean^{12,14}. Under SSP585, the constrained ensemble projects a $53.4 \pm 16.0\%$ weakening by 2091–2100 relative to 1950–2000, in close agreement with the approximately 50% weakening estimated by Portmann et al.¹⁴ from an independent observationally constrained analysis. This agreement provides additional support for the view that models capable of reproducing observed AMOC-related fingerprints may exhibit greater sensitivity to anthropogenic forcing than the Full CMIP6 ensemble. Our results, however, contrast with the more moderate weakening inferred by Bonan et al.¹², who found that observational constraints imply a limited future AMOC decline.

The discrepancy may arise from differences in the observational metrics used to constrain model projections. While Bonan et al.¹² constrained AMOC sensitivity using present-day circulation characteristics, our approach is based on the observed relationship between AMOC variability and dynamic sea-level (DSL) change along the North Atlantic boundary. The stronger weakening obtained here suggests that AMOC–DSL coupling may preferentially identify models with a larger forced response. The enhanced weakening in the constrained ensemble is also consistent with studies highlighting substantial inter-model differences in the mechanisms governing future AMOC decline. Baker et al.¹⁵ showed that projected weakening depends strongly on overturning pathways and the balance between density-driven and wind-driven circulation changes, implying that observational constraints may preferentially select models with circulation structures that are more susceptible to greenhouse-gas forcing. Similarly, Devilliers et al.¹³ showed that constraining CMIP6 models using an observationally derived AMOC–SST relationship led to a more realistic representation of Atlantic Water transport into the Arctic and substantially modified future projections relative to the Full CMIP6 ensemble. Their findings demonstrate that physically grounded observational constraints can effectively reduce structural model uncertainty. Our results extend this concept by showing that dynamic sea-level fingerprint of AMOC variability provides an independent observational constraint that likewise selects models with greater historical fidelity and projects a substantially stronger future AMOC decline.

The scenario dependence of the projections further highlights the importance of applying observational constraints to future AMOC estimates. While both SSP585 and SSP126 projects continued AMOC weakening consistent with previous studies^{13–15} and²³, the constrained ensembles systematically produce stronger declines than the Full CMIP6 ensemble within each scenario. Under the high-emission SSP585 scenario, the constrained ensemble projects a substantially stronger AMOC decline than the Full CMIP6 ensemble, with a weakening trend of $-1.02 \text{ Sv decade}^{-1}$ during 2015–2100 compared with $-0.85 \text{ Sv decade}^{-1}$ in the Full CMIP6 projections. This stronger decline is reflected in the end-of-century AMOC reduction, which reaches $53.4 \pm 16.0\%$ relative to the 1950–2000 baseline in the constrained ensemble, compared with $45.3 \pm 20.3\%$ in the Full CMIP6 ensemble. Similarly, under the lower-emission SSP126 scenario, the constrained ensemble projects a weakening trend of $-0.58 \text{ Sv decade}^{-1}$ and a total reduction of $36.0 \pm 20.9\%$, whereas the Full CMIP6 ensemble projects a weaker trend of $-0.44 \text{ Sv decade}^{-1}$ and a reduction of $29.0 \pm 22.0\%$. The uncertainty ranges represent ± 1 standard deviation of the model-specific percentage weakening and therefore quantify inter-model spread within each ensemble. The relatively large spread reflects substantial differences among CMIP6 models in the magnitude of projected AMOC weakening, highlighting the persistent uncertainty associated with future overturning circulation projections. Nevertheless, the consistent tendency for the constrained ensemble to project larger AMOC declines across both emission pathways indicates that the observational constraint preferentially selects models with greater sensitivity to anthropogenic forcing. Consequently, Full CMIP6 ensembles may underestimate the magnitude of future AMOC weakening, particularly under scenarios of continued high greenhouse-gas emissions.

Several limitations should nevertheless be acknowledged. First, the observational AMOC record remains relatively short, limiting the calibration period available for evaluating long-term variability. Second, tide-gauge observations may still contain residual influences from vertical land motion and local coastal processes despite trend correction. Third, the constraint framework is based on a selected subset of models that reproduce the observed AMOC–DSL relationship rather than a formal probabilistic emergent constraint. Consequently, the constrained projections should be interpreted as observationally informed model selection rather than a fully independent statistical prediction framework.

Overall, this study demonstrates that sea-level observations provide a physically interpretable and observationally grounded metric for evaluating AMOC behaviour in climate models and that coastal sea level can be used to understand AMOC evolution. By linking western North Atlantic sea-level gradients to overturning circulation variability, the proposed constraint framework improves representation of historical AMOC evolution and reduces uncertainty in future projections. These findings highlight the potential value of long-term coastal sea-level observations for constraining large-scale ocean circulation change and improving confidence in projections of future climate and regional sea-level risk.

Data

CMIP6 historical simulations

We analyse historical and future simulations (ScenarioMIP) from 20 models (Table S1) participating in the Coupled Model Intercomparison Project Phase 6, CMIP6²⁴. For each model, we use the first ensemble member (r1i1p1f1) except for UKESM1-0-LL, where we used (r1i1p1f2) for the AMOC estimates¹⁷ and dynamic sea level (DSL). All model output is regridded to a common $2.5^\circ \times 2.5^\circ$ horizontal grid using conservative remapping to ensure spatial consistency.

Monthly DSL data were averaged into annual means with the global mean subtracted to isolate regional dynamic sea-level variability associated with ocean circulation changes rather than the externally forced global mean rise. We analyzed changes over the North Atlantic domain (90°W – 0° , 0° – 60°N), computing both regional spatial patterns and time series by averaging the DSL over this region from 1850 to 2014. These series assessed temporal trends and inter-model spread in regional dynamic sea level variability.

For AMOC strength and variability, monthly AMOC estimates were obtained according to¹⁷ at latitude 26.5°N for each year. Anomalies were calculated relative to the 1850–2014 mean and smoothed using a 5-year moving average.

To examine the link between AMOC strength and dynamic sea level (DSL) for each model, the spatial correlation between AMOC change and DSL was computed using Pearson correlation across all grid cells. Statistical significance of the correlations was assessed at each grid cell using a two-tailed t-test ($p < 0.05$). Lagged correlations were performed between the AMOC estimate and the DSL gradient. Only positive lags were used (i.e., AMOC leading the DSL). For each model, the lag with maximum correlation

was identified, and spatial maps of the maximum correlation and corresponding best lag were generated. Ensemble maps of maximum correlation, best lag, and significance were created by averaging model-specific maps.

Observational data

We combine three independent observational datasets:

1. **Satellite altimetry:** Gridded sea surface height (SSH) anomalies for 1993–2019 were obtained from the Copernicus Marine Service global multi-mission altimetry product ²⁵. The SSH gradient index was defined analogously to the DSL gradient index by averaging SSH anomalies over the southern (29–39°N, 75–55°W) and northern (43–53°N, 58–38°W) western North Atlantic regions.
2. **Tide gauge records:** Monthly Revised Local Reference (RLR) tide-gauge records were obtained from the Permanent Service for Mean Sea Level (PSMSL) ²⁶ (accessed 21 October 2024). Tide-gauge stations along the western North Atlantic coastline (24°–43°N, 82°–70°W) were selected based on record length (> 40 years) and data completeness. A linear regression model was used to estimate and remove the pressure-driven component of sea-level variability. Fernandina Beach (Florida) and Sandy Hook (New Jersey) were identified as the stations that best represent the southern and northern coastal sea-level variability (Supplementary 3), respectively. They were used to construct the tide-gauge sea-level gradient index.
3. **AMOC estimates from reanalysis:** Observational estimates of the Atlantic Meridional Overturning Circulation (AMOC) at 26°N were obtained from the Copernicus Marine Service product *GLOBAL_OMI_NATLANTIC_amoc_26N_profile* ²⁷, which provides monthly estimates of AMOC variability derived from ocean reanalysis and observational constraints.

Methodology

Regional DSL variability in the southern (29–39°N, 75–55°W) and northern (43–53°N, 58–38°W) North Atlantic was compared with nearby tide-gauge records to identify stations that best represent the large-scale coastal signal. Fernandina Beach and Sandy Hook exhibited the strongest correspondence with the southern and northern SSH regions, respectively (Supplementary Fig. 3). To ensure consistency between coastal and open-ocean variability, the linear trend of each tide-gauge record was adjusted over the satellite era (1993–2019).

The coastal tide-gauge (TG) gradient index was then defined as the difference between the adjusted southern (Fernandina) and northern (Sandy Hook) tide-gauge records, analogous to the satellite-derived SSH gradient index as shown in Eq. 1:

$$\Delta \eta_{\text{coast}} = \eta_{\text{south}} - \eta_{\text{north}}$$

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where η_{south} and η_{north} represent corrected tide gauge at Fernandina Beach and Sandy Hook, respectively. This gradient reflects variations in the large-scale pressure field associated with western boundary geostrophic transport. To suppress high-frequency variability, all-time series were smoothed using a 5-year moving average.

Missing values in the tide gauge records were infilled using a regression-based approach during the satellite era. For each station, a linear model was fitted between the tide gauge record and the corresponding regional SSH index using overlapping, non-missing data. The fitted relationship was then used to estimate missing values. Where insufficient overlap existed, missing values were filled using nearest-neighbour interpolation. This approach ensures continuity while minimizing the introduction of artificial variability.

The relationship between the sea-level gradient and AMOC strength was calculated using observations from the Copernicus at 26.5°N. A linear regression model was used, Eq. 2.

$$\text{AMOC}(t) = \alpha \cdot \Delta \eta(t)$$

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where α is a scaling coefficient estimated over the overlap period (1993–2014). The calibrated relationship was then applied to the full tide gauge record to reconstruct AMOC variability back to the early 20th century.

Figure 6 shows the lagged correlations between AMOC anomalies and the DSL index, and the AMOC–DSL index correlations, in CMIP6 models vs observations. Lagged correlation analysis (Fig. 3a) demonstrates that AMOC and coastal sea-level covary in most of the CMIP6 models, but AMOC lead in 5 models (HadGEM3-GC31-LL, HadGEM3-GC31-MM, E3SM-1-1, FIO-ESM-2-0, CNRM-CM6-1-HR) along the mid-Atlantic coast and decrease towards high latitudes.

To compare the AMOC-DSL gradient relationship for both CMIP6 and Observe, we used the observed AMOC–DSL gradient correlation (r_{obs}) as a benchmark. To compare the AMOC–DSL coastal relationship in CMIP6 models with observations, the observed maximum lagged correlation (r_{obs}) is used as a reference benchmark. To quantify observational uncertainty, we performed 1000 block-bootstrap resamples of the observed AMOC and sea-level time series using a block length of five years, consistent with the temporal smoothing applied in the analysis. For each bootstrap realization, the lagged AMOC–DSL correlation was recomputed and the maximum correlation retained. The standard deviation of the resulting bootstrap distribution was used as an estimate of observational uncertainty. We then evaluated each CMIP6 model against the observed maximum lagged correlation using a Gaussian likelihood function. This approach assigns the highest weight to models whose simulated correlations closely match the observations and progressively lower weights to models that diverge from

the observed relationship (Fig. 3b). Models with weights exceeding 10% of the maximum ensemble weight are classified as constrained (blue), indicating relatively strong agreement with observations within the bootstrap-derived uncertainty framework. Models below this threshold (red) show weaker consistency and are considered unconstrained. The constrained models better reproduce the observed correlation structure, including positive correlations in the subtropical gyre and negative correlations elsewhere, whereas unconstrained models show weaker agreement.

Code: All analyses and figures were computed and plotted using Matlab (<https://www.mathworks.com/products/matlab.html/>). The code used for the analysis in this study will be available on a GitHub repository when the paper is published

Declarations

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Author's contribution: The manuscript concept was designed by E.O.E., G.D.M., and J.M. Data curation by E.O.E, J.M., G.H., and P.M. Data analysis was performed by E.O.E. with the support of G.D.M and H.Y. Visualization and original draft writing were carried out by E.O.E. The manuscript was reviewed and edited by G.D.M., H.Y., and P.M. All authors discussed the study results and reviewed the final manuscript.

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Figures

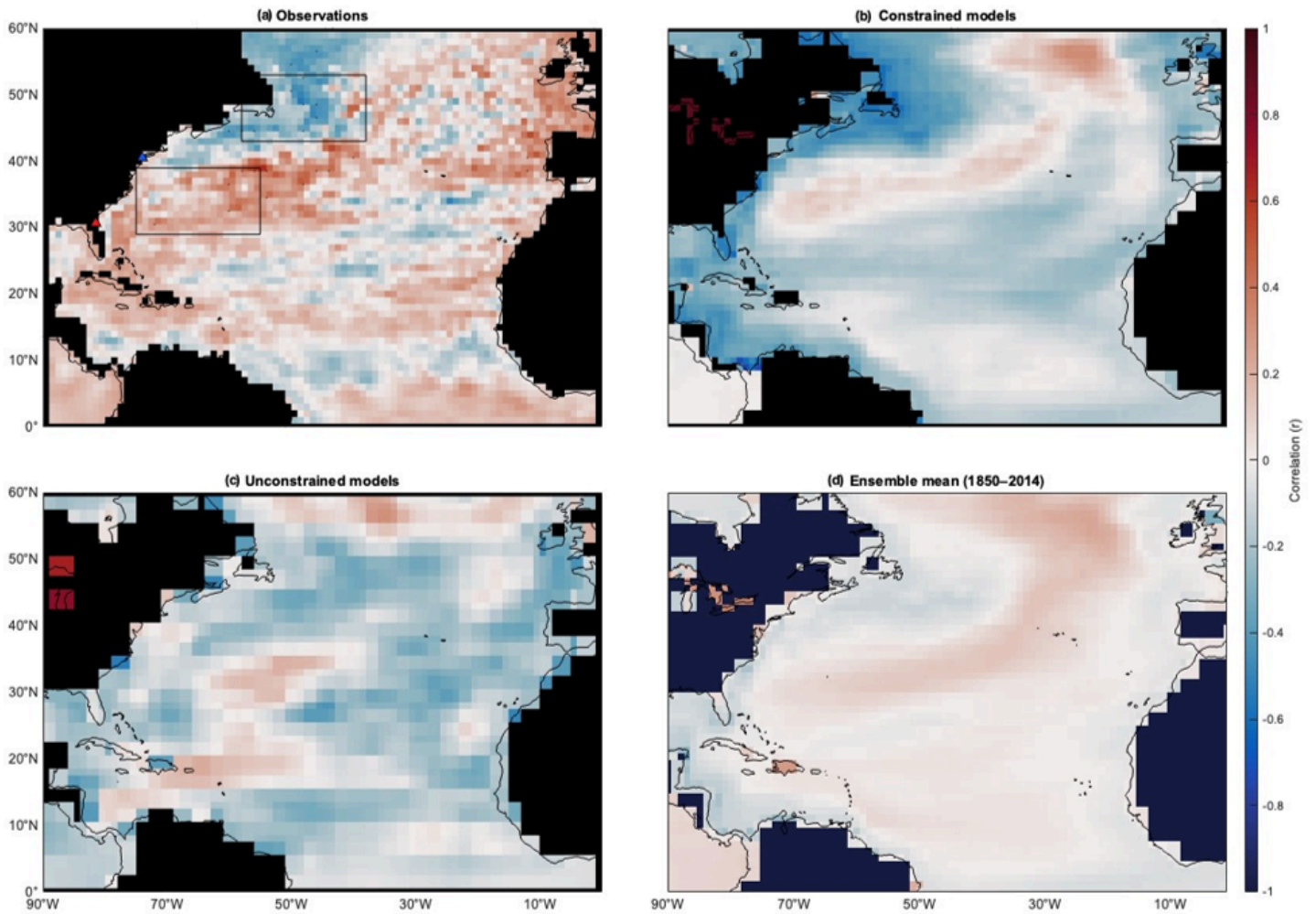


Figure 1

Spatial correlations between the Atlantic Meridional Overturning Circulation (AMOC) and dynamic sea level anomalies (DSL) across the North Atlantic. Panels (a–c) show correlations for the 1993–2014 period, including (a) observations, (b) the ensemble mean of CMIP6 constraint models, (c) the ensemble mean of unconstrained models, and (d) the multi-model ensemble mean 1850–2014. Colours indicate the correlation coefficient (r), with positive (red) and negative (blue) correlations illustrating the spatial sea-level response associated with AMOC variability. The boxes in panel (a) highlight the northern and southern coastal regions along the western Atlantic Ocean used for regional sea-level analysis. The red and blue triangles represent the tide gauges used, Fernandina (south) and Sandy Hook (North), respectively, used to construct the tide gauge gradient index.

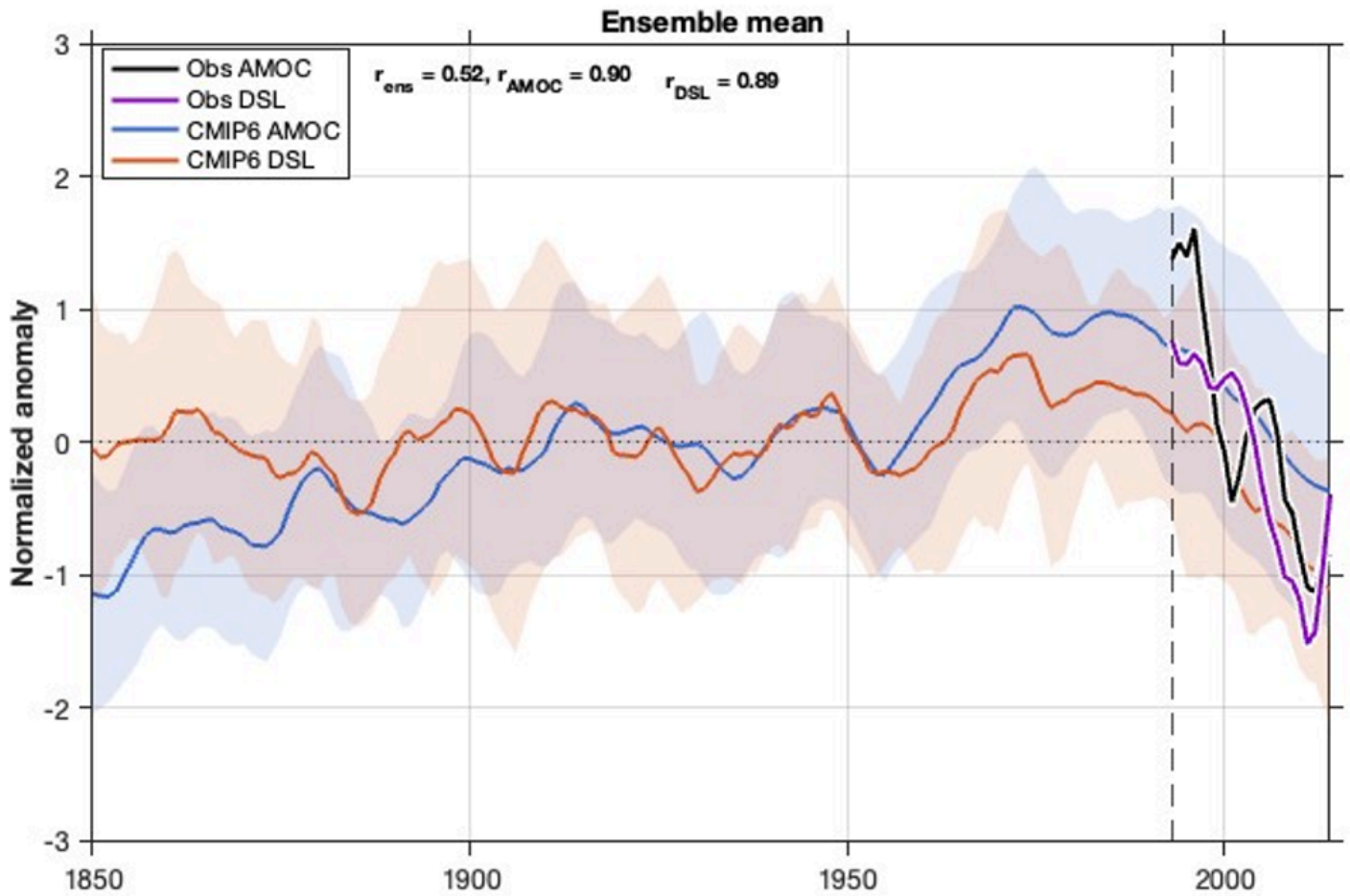


Figure 2

Normalized annual CMIP6 ensemble AMOC anomalies (blue) and the DSL gradient index (red), defined as the difference between dynamic sea level anomalies averaged over the southern (29–39°N, 75–55°W) and northern (43–53°N, 58–38°W) North American Atlantic coast (red) during 1850–2014, with correlation coefficients. Dashed lines denote zero anomalies. Observed AMOC (black) and DSL gradient index (purple) for 1993–2014 are overlaid on the ensemble panel. The CMIP6 ensemble mean exhibits strong agreement with observations for both AMOC variability ($r=0.90$) and the DSL index ($r=0.89$), supporting the robustness of the observed AMOC–DSL relationship.

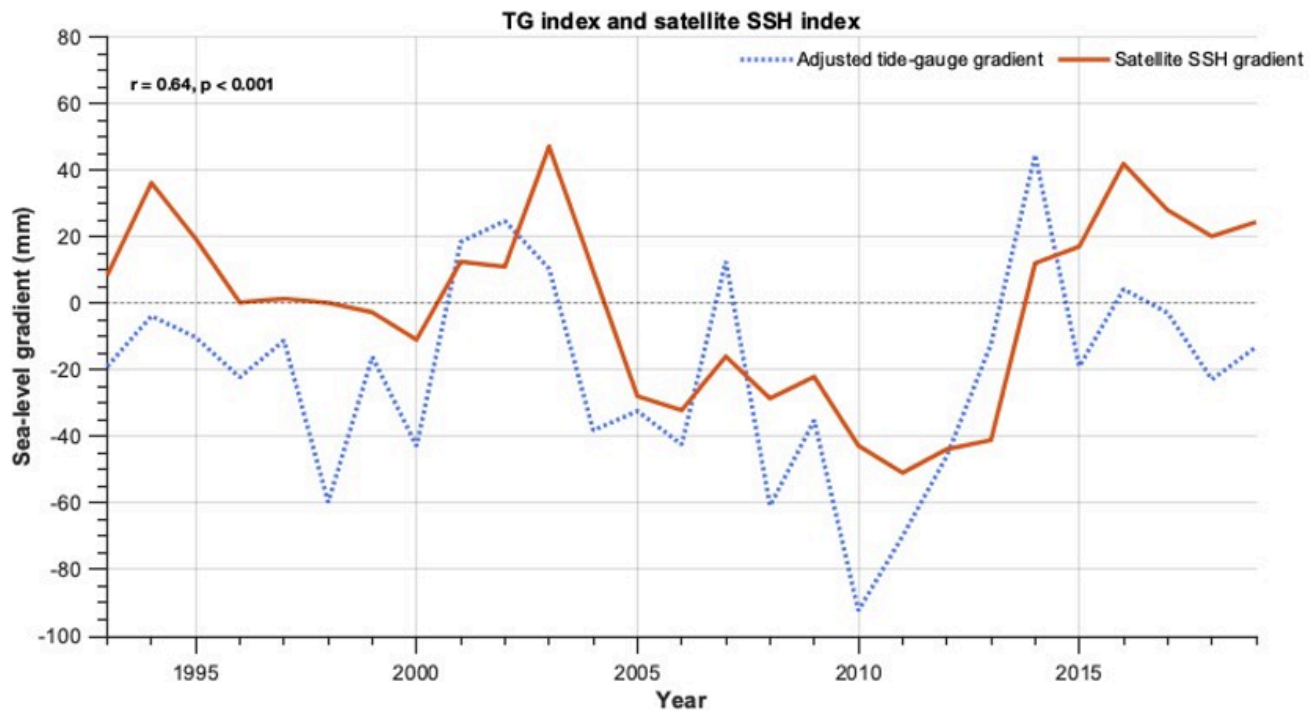


Figure 3

Comparison of tide-gauge-derived and satellite-derived dynamic sea-level indices in the western North Atlantic (1993–2019). Adjusted tide-gauge (dashed line) and satellite SSH (solid line) gradient indices showing consistent variability ($r = 0.64, p < 0.001$) associated with AMOC changes. The tide gauge gradient is the difference between Fernandina and Sandy Hook.

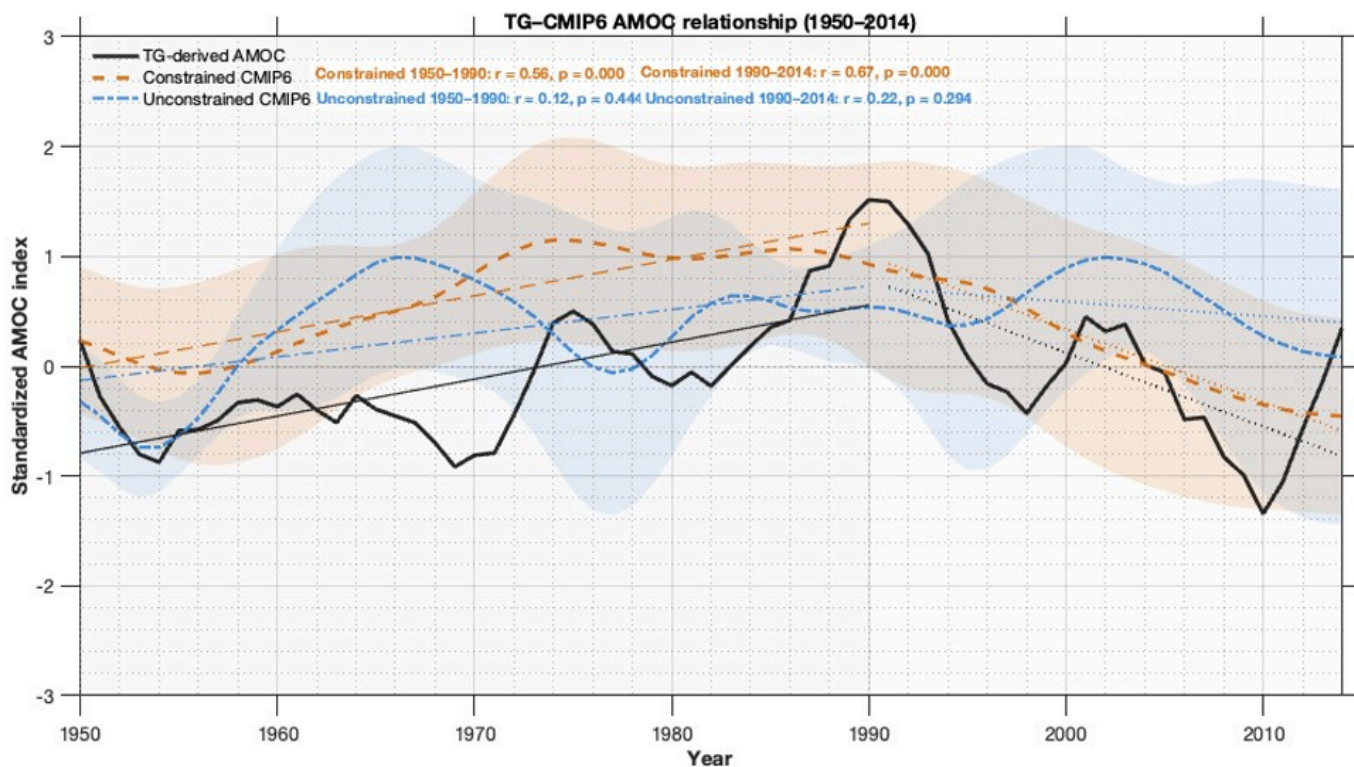


Figure 4

Comparison of tide-gauge-derived and CMIP6-simulated AMOC (1950–2014). Standardized AMOC anomalies from tide gauges (black) and CMIP6 ensembles (constrained: orange; unconstrained: blue). Lines show 5-year smoothed series; shading indicates ± 1 ensemble standard deviation. Dashed and dotted lines show linear trends for the two sub-periods, 1950–1990 and 1990–2014, respectively. Correlation coefficients and associated p-values for each period are shown within the panels

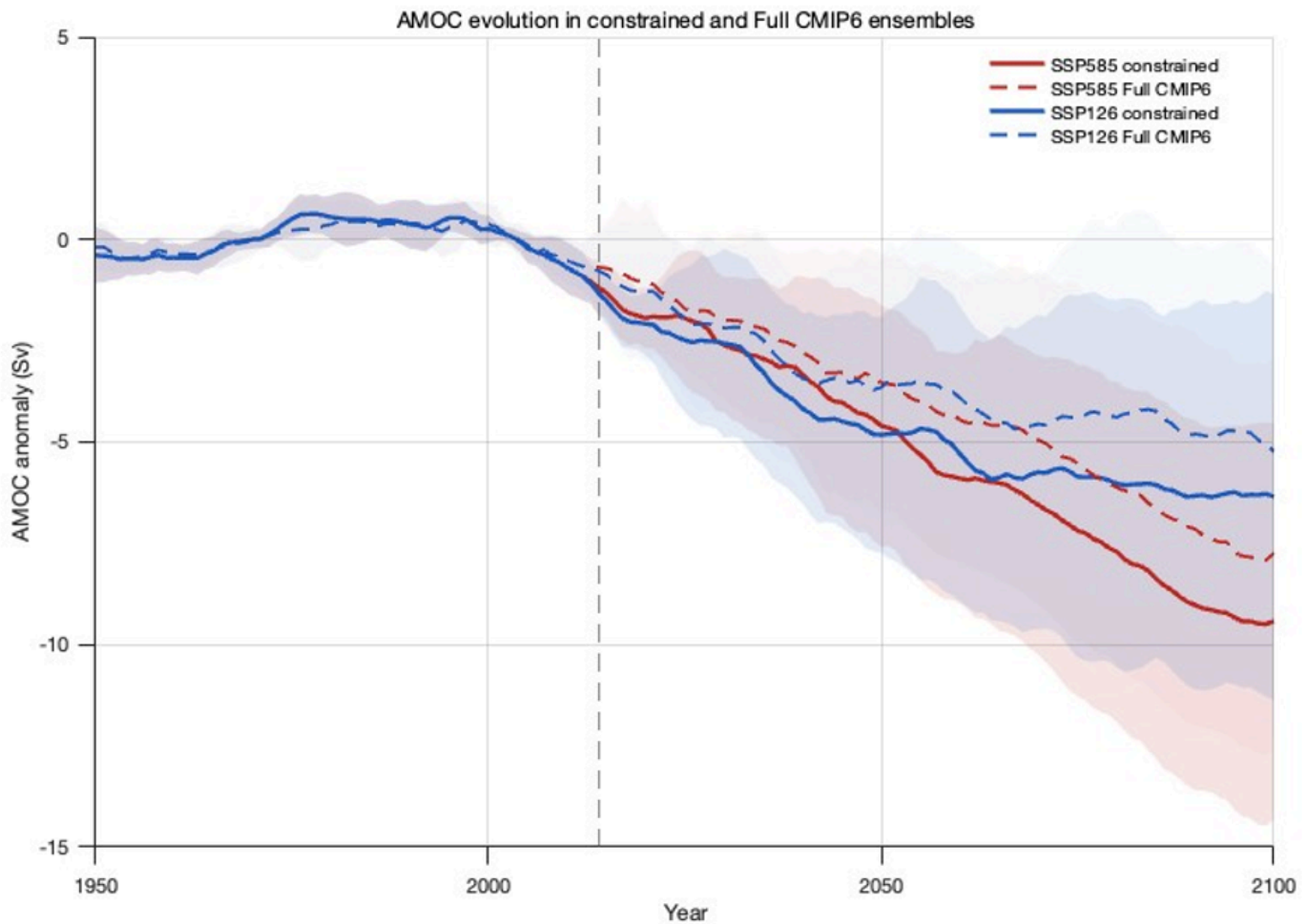


Figure 5

Constrained and Full CMIP6 ensemble projections of Atlantic overturning circulation under future climate forcing. Time series of the Atlantic Meridional Overturning Circulation (AMOC) strength at 26.5°N from 1950–2100 derived from CMIP6 simulations. Anomalies are calculated relative to the 1950–2014 historical mean and smoothed with a 5-year running mean. Solid lines show ensemble means from the constrained model subset, whereas dashed lines show the corresponding Full CMIP6 ensemble means. Red and blue curves represent projections under SSP585 and SSP126 forcing scenarios, respectively. Shaded envelopes denote ± 1 standard deviation across models. The vertical dashed line indicates the start of future scenario integrations after 2014.

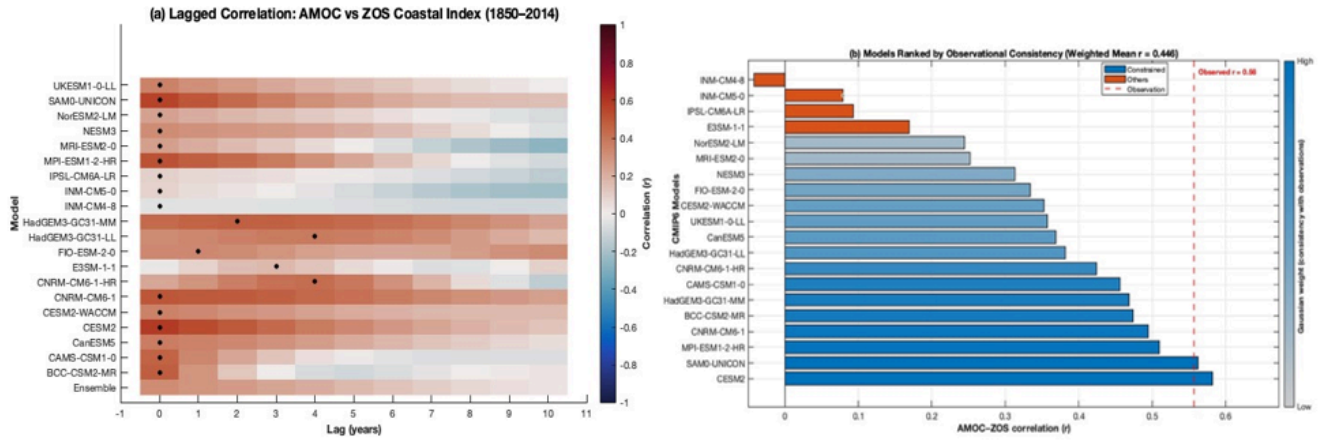


Figure 6

(a) Lagged correlations between AMOC anomalies and the coastal DSL index for the ensemble mean and individual CMIP6 models. Only positive lags are shown. Colours indicate autocorrelation-adjusted correlation coefficients, and black dots mark the lag of maximum positive correlation for each model. Colours denote correlation strength, (b) AMOC–DSL correlations in CMIP6 models compared with observations. Bars show model correlations; colour indicates Gaussian weight (blue = high, red = low) based on bootstrap-derived observational uncertainty. The red dashed line marks the observed correlation. Models above the weight threshold are classified as constrained, and the weighted mean correlation is reported.