



How robust are observational constraints on future AMOC changes?

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Abstract. The Atlantic Meridional Overturning Circulation (AMOC) is a key component of the climate system, transporting heat northward in the Atlantic Ocean. A decline in the AMOC is expected under increasing greenhouse gas concentrations, but large uncertainties remain in the magnitude of this weakening and its associated climate impacts across climate models. Observational constraints based on direct AMOC observations and various AMOC fingerprints have recently been developed to reduce these uncertainties. However, these constraints can be strongly affected by low-frequency internal variability, particularly given the short observational record, as well as measurement errors. Here, we use an innovative method based on Bayesian statistics, with a comprehensive treatment of these uncertainties, to assess the ability of direct observations and AMOC fingerprints to constrain the AMOC weakening in climate projections, and provide up-to-date information about the AMOC forced response. Using direct AMOC observations leads to a larger projected weakening of 15 -46.6% $[-26.5; -66.7]$ compared to -42.7% $[-19.4; -64.8]$ for the unconstrained projections. However, this constraint is highly sensitive to internal variability, and longer observations are needed to provide a more robust constraint. We further show that considering AMOC fingerprints, which provide longer observation records, does not reduce the uncertainty within the AMOC constrained projections as the associated forced response depends strongly on the fingerprint considered. Despite differences among constraints, none indicate an AMOC collapse (i.e. 80% AMOC weakening) before the end of the 21st century. Nevertheless, all constraints point towards substantial weakening (i.e. 50% AMOC weakening), with potentially strong climate impacts.

1 Introduction

The Atlantic Meridional Overturning Circulation (AMOC) plays a crucial role in both local and global climate, by transporting heat from the South Atlantic to the North Atlantic and sequestering anthropogenic carbon and heat in the deep ocean (Buckley and Marshall, 2016). It is estimated that the AMOC transports about 0.5 PW of heat from the equator annually into the North Atlantic, which represents roughly two third of the oceanic northward heat transport at northern latitude (Trenberth et al. 2019), warming the Northern Hemisphere more than the Southern Hemisphere and moving the Inter-Tropical Convection Zone (ITCZ) northward, which influence global rainfall and atmospheric circulation pattern (Fierson et al. 2013; Marshall et al. 2014). Change in the AMOC strength is thought to be an important driver of the change in North Atlantic Sea Surface Temperature (SST) (Rahmstorf et al. 2015; Zhang et al. 2019), influencing a large range of phenomena, such as the number of hurricanes hitting the southwest american coast (Yan et al. 2017), the Sahel monsoon (Zhang and Delworth, 2006), the Atlantic storm tracks (Woollings et al. 2012). It also influences the variability in Arctic sea ice (Mahajan et al. 2011), which has been linked with midlatitude climate variability (Screen et al. 2018).

A decline of the AMOC is expected in response to increased greenhouse gas concentrations (Weijer et al. 2020). This decline, however, varies substantially across climate models, with model uncertainty accounting for approximately 75% of



the total uncertainty in the end of the 21st century (Portmann et al., 2026) for high emission scenarios. This leads to large uncertainties in climate responses. Climate models with the largest AMOC decline are characterized by minimal North Atlantic warming relative to the pre-industrial period, a southward displacement of the ITCZ, and a poleward shift of the mid-latitude jet, whereas models with the smallest AMOC decline exhibit greater North Atlantic warming, a wet-get-wetter and dry-get-drier precipitation pattern over the northern hemisphere, and smaller displacements of the mid-latitude jet (Bellomo et al. 2021). This large inter-model spread in the AMOC decline also seems linked to the climate feedback parameter inter-model spread, suggesting that constraining future ocean circulation changes would be necessary for accurate climate projections (Lin et al. 2019). Moreover, several studies, warn of the risk of an AMOC collapse (a weakening of at least 80% of the current estimated amplitude from observations) or the reaching of a tipping point (an abrupt and irreversible change) in the AMOC during the 21st century or beyond (Boers 2021, Ditlevsen and Ditlevsen 2023, van Westen et al. 2024, Drijfhout et al. 2025). The concept of observational constraints aims at reducing the uncertainty in the projections of the forced climate response simulated by model ensembles (Hall et al., 2019; Brient, 2020). Applying these techniques on the future AMOC changes is therefore of primary interest, in order to better assess the future changes of the AMOC and the related climate impacts.

Based on the relationship between the AMOC strength and the 21st century AMOC decline, Weijer et al. (2020) developed an emerging constraint using the Rapid Climate Change-Meridional Overturning Circulation and Heatflux array (RAPID; Frajka-Williams et al. 2019) that continuously monitors the AMOC at 26°N since April 2004. Their results suggest a decline of 8 Sv (45 %) of the AMOC by 2100 using SSP5-8.5, with a range of 6 Sv (35%) to 11 Sv (63%) based on the 95 % confidence interval. This decline is stronger in the last generation of climate models, from the phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016) than the previous one (CMIP5; Taylor et al. 2012). Recently, Bonan et al. (2025) developed an emerging constraint using a thermal-wind expression that relates the AMOC strength to the meridional density difference and the overturning depth in the Atlantic. By using RAPID and ECCOV4r3 dataset (Forget et al., 2015), they conclude that the AMOC will experience a limited weakening of about 3–6 Sv (about 18–43%) by the end of this century, regardless of emissions scenario. However, using direct AMOC observations on emerging constraint of the AMOC can be misleading, as they are only available over a short amount of time (20 years), which can be largely influenced by the low-frequency internal climate variability of the AMOC found in some CMIP6 models (Bonnet et al. 2021).

Various AMOC fingerprints, based on variables that can be derived from both climate models and observations, have been proposed to better understand and constrain the historical evolution of the AMOC and detect its weakening (Jackson and Wood, 2020). For example, Bonnet et al. (2021) investigated the respective contributions of internal variability and the forced response to the AMOC decline over the twentieth century, as suggested by Caesar et al. (2018), using four different AMOC fingerprints in a large ensemble of climate simulations. Similarly, Menary et al. (2020) used AMOC fingerprints to constrain the forced AMOC response over the historical period. They showed that the AMOC strengthening up to 1985, associated with the stronger anthropogenic aerosol forcing simulated on average in CMIP6 compared with CMIP5, may have been overestimated. Baker et al. (2023) used global ocean reanalyses to constrain projected AMOC changes by the end of



the twenty-first century based on the strength of the Indo-Pacific pathway of the AMOC. They estimated an AMOC weakening of 29–61% under the SSP5-8.5 scenario by 2100. Building on these approaches, Portmann et al. (2026) evaluated four different constraining methods and found, through a perfect-model evaluation, that the most effective approach combined information from RAPID AMOC observations with temperature and salinity data using a multivariate ridge-regularized linear regression. This method leads to a strong constraint on the AMOC slowdown, of $51 \pm 8\%$ (90% probability) relative to the 1850–1900 period using SSP2-4.5. However, this method does not take into account the internal variability, nor the measurement error in the statistical technique, that can strongly impact the constraints.

In this study, we use AMOC observations as well as several of its available fingerprints and a comprehensive treatment of uncertainties to constrain AMOC projections simulated by the CMIP6 models, meaning reducing uncertainties in the AMOC response to all external forcings. Our estimates of the constrained projections come from the Kriging for Climate Change (hereafter KCC) method (Ribes et al., 2021), largely used for several applications (Qasmi and Ribes 2022, Douville and Willett 2023, Douville and Allan 2026, Forster et al 2026), which interpolates observations and climate models. The objective of this study is to shed new light on the capacity of the observed AMOC, as well as several AMOC fingerprints, to constrain the uncertainties associated with the decline of the AMOC and therefore to provide up-to-date information about the forced response of the AMOC.

2 Data and Method

2.1 CMIP6 models

We used 143 simulations from 28 models from CMIP6 (Eyring et al., 2016) to estimate the AMOC forced response over the 1850-2100 period (Table S1): historical simulations over the 1850-2014 period and the Shared Socioeconomic Pathway (SSP) 5-8.5 scenario projections since 2015 (O’Niell et al. 2016). The AMOC is defined as the maximum of the annual Atlantic meridional stream function at 26°N.

2. AMOC fingerprints

In this study, 3 fingerprints are used to constrain the AMOC decline at 26°N over the 21th century in the CMIP6 multi-model ensemble. All these fingerprints have already been used in previous studies. They are all expressed in terms of a temporal index.

1. The first index is based on the average North Atlantic Subpolar Gyre SST relative to the global SST from November to May following Caesar et al. (2018) (hereafter C-index), with a colder SST over this region associated with a decrease of the AMOC.



2. The second index is based on the difference in annual mean SSTs averaged over the regions 40°–60°N, 60°–10°W and 40°–60°S, 50°W–0°, following Latif et al. (2006) (hereafter L-index), and reflects changes in the interhemispheric oceanic heat redistribution associated with AMOC variability.
3. The third index is based on the Interhemispheric Global Mean Surface Temperature (GSAT) (hereafter I-index), with a decrease of the AMOC that is associated with a cooling in the Northern Hemisphere in comparison to the Southern Hemisphere (Liu et al. 2020). Differences in interhemispheric GSAT have also been found in response to the intensity of the warming hole (Park et al., 2024), which may be associated with the changes in the AMOC forced response (Li and Liu, 2025)

For the AMOC fingerprints based on SST the HadISST (Rayner et al. 2003) dataset is used. The third AMOC fingerprint based on GSAT is calculated from the HadCRUT5 (Morice et al. 2021) dataset. To maximize the number of climate models included in the analysis, we focus exclusively on SST-based fingerprints and exclude salinity-based fingerprints, as salinity data are available for fewer models, which can provide a robust estimate of future changes estimated by the constraint method

Observations of the AMOC are also available (RAPID; Frajka-Williams et al. 2019) but over a relatively short period in comparison the AMOC variability. These observations are also used in this study as a benchmark to assess the added-value of the fingerprints and their uncertainties which, by construction, sample a longer historical period.

3. Constraining projections

To assess past and future forced response of the AMOC, we use the KCC observational constraint method that has been previously applied to global mean warming (Ribes et al., 2021) and regional warming (Qasmi and Ribes, 2022; Qasmi, 2023). This technique works in several steps. First, the forced response of the AMOC is estimated in each climate model over the 1850-2100 period by averaging all available ensemble members. This ensemble mean estimate of the forced response is further smoothed using a Generalized Additive Model (GAM), following Qasmi and Ribes (2022) to minimize internal variability as much as possible within each model. The response to natural forcings, including volcanic eruptions, is estimated using a two-layer energy balance model (Geoffroy et al., 2013), while the response to anthropogenic forcings is represented by smoothing splines. This sample of the forced responses from the CMIP6 models is used to derive a gaussian distribution with given non-stationary mean and covariance, which is considered as a prior of the real-world forced response. This is done assuming that “models are statistically indistinguishable from the truth”. Third, observations are used to derive a posterior distribution of the past and future forced response given observations, using the Bayesian theorem. This procedure can be summarized using the equation:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \boldsymbol{\varepsilon}, \quad (1)$$

where $\mathbf{y}$ is the time series of observations (a vector), $\mathbf{x}$ is the time series of the forced response (a vector) simulated by the CMIP6 models over 1850-2100, $\mathbf{H}$ is an observational operator (matrix), and $\boldsymbol{\varepsilon}$ is the random vector noise associated with



130 internal variability and measurement errors. We suppose that $\boldsymbol{\varepsilon}$ follows a multivariate Gaussian distribution with a mean of 0 and a covariance $\boldsymbol{\Sigma}_y$ which accounts for the uncertainty related to internal variability, which is assumed to be the sum of two AR1 processes, following Qasmi and Ribes (2022). The observational operator $\mathbf{H}$ is a matrix which extracts the components of $\mathbf{x}$ that are observed in $\mathbf{y}$, thus all $\mathbf{H}$ coefficients are equal to 0 or 1. Climate models are used to derive the gaussian prior on $\mathbf{x}$, noted :

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$$\Pi(\mathbf{x}) = N(\boldsymbol{\mu}_x, \boldsymbol{\Sigma}_x), \quad (2)$$

$\boldsymbol{\mu}_x$ and $\boldsymbol{\Sigma}_x$ are estimated as the sample mean and sample covariance across the CMIP6 models after applying the GAM on the ensemble means. The posterior distribution given observations $\mathbf{y}$, i.e. the constrained distribution, is $p(\mathbf{x}|\mathbf{y}) = N(\boldsymbol{\mu}_p, \boldsymbol{\Sigma}_p)$ can be derived analytically. In this paper, we aim at estimating the forced response of the AMOC assumed to be correlated to each fingerprint (Figure 3). We take advantage of these tight links that exist between the AMOC fingerprints (for which longer observations are available) and the AMOC itself to constrain the AMOC forced response both in the past and in the future. Therefore:

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$$\mathbf{x} = (\mathbf{x}_{\text{mod}}^{\text{AMOC}}, \mathbf{x}_{\text{mod}}^f), \quad (3)$$

where each element of $\mathbf{x}$ is the annual forced response over the 1850–2100 period. $\mathbf{x}_{\text{mod}}^{\text{AMOC}}$ and $\mathbf{x}_{\text{mod}}^f$ stand for the AMOC and fingerprint time series, respectively. The length of $\mathbf{x}$ is thus 502. Similarly,

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$$\mathbf{y} = \mathbf{y}_{\text{obs}}^f, \quad (4)$$

where the observed time series of the fingerprint is used in $\mathbf{y}$.

A constraint based on RAPID observations only is also used as a benchmark to estimate the sensibility of the constraints to the treatment of internal variability. For this specific case, $\mathbf{x} = \mathbf{x}_{\text{mod}}^{\text{AMOC}}$ and $\mathbf{y} = \mathbf{y}_{\text{obs}}^{\text{AMOC}}$.

The reader is directed to Qasmi and Ribes (2022) for a comprehensive description of the method.

150 The performance of the method is evaluated using the Continuous Ranked Probability Scores (CRPS, Hersbach, 2000) in an idealised framework described in section 3.1. It is defined as the quadratic measure of discrepancy between (i) $1(x \geq y_{\text{ref}})$, the empirical cumulative distribution function (CDF) of a scalar reference y_{ref} simulated by one model member and averaged over a given future period, and (ii) the projected CDF of $p(\mathbf{x}|\mathbf{y}_{\text{ref}})$ (i.e. the constrained distribution) over the same period.

155 3 Results

3.1 Sensitivity of the constraint to the internal variability

When using the full observational AMOC record to constrain the forced AMOC changes, only the upper part of the uncertainty range is ruled out (Figure 1a). However, the observational record remains short in comparison to the low-frequency internal variability of the AMOC. To assess the sensitivity of this result to internal variability, we used the models exhibiting the smallest (GISS-E2-1-G) and largest (NorESM2-LM) variance as lower and upper estimates of AMOC internal



variability from the associated pre-industrial control simulations. The inferred constraint on the forced AMOC changes is strongly affected by this choice, with weaker internal variability leading to a substantially tighter constraint (Figure 1b), whereas stronger internal variability results in only a limited reduction in uncertainty (Figure 1c). These results show the limited added value from using AMOC observations only to constrain its future changes as internal climate variability (i) can not be comprehensively estimated from the sole observations and (ii) estimated from climate models can be largely different from one to another.

To go further and evaluate how having more years would lead to a better constraint on the AMOC forced changes, we adopt a perfect-model framework in which one CMIP6 simulation over 1850–2100 is selected as the reference. We then consider two periods as pseudo-observations, corresponding to the available observational record (2004–2025) and an extended period (2004–2050).

We then apply the KCC method to constrain the forced AMOC changes over 2081–2100 relative to the SSP5-8.5 scenario from all of the other models to construct the real-world forced response. This is done for each member of each CMIP6 model. The CRPS values are finally calculated, one for the 2081–2100 AMOC changes constrained by the pseudo-observation and one for the unconstrained AMOC changes. The associated skill score defined as :

$$\text{CRPSS} = 1 - \text{CRPS}_{\text{constrained}} / \text{CRPS}_{\text{unconstrained}}, \quad (5)$$

quantifies the performance of the KCC method and its added value. A negative score means that the estimated AMOC changes after constraint are less accurate than the unconstrained ensemble, a null score means that the method has no benefit, and a positive score means that the estimates of the changes are more accurate compared to the unconstrained ensemble.

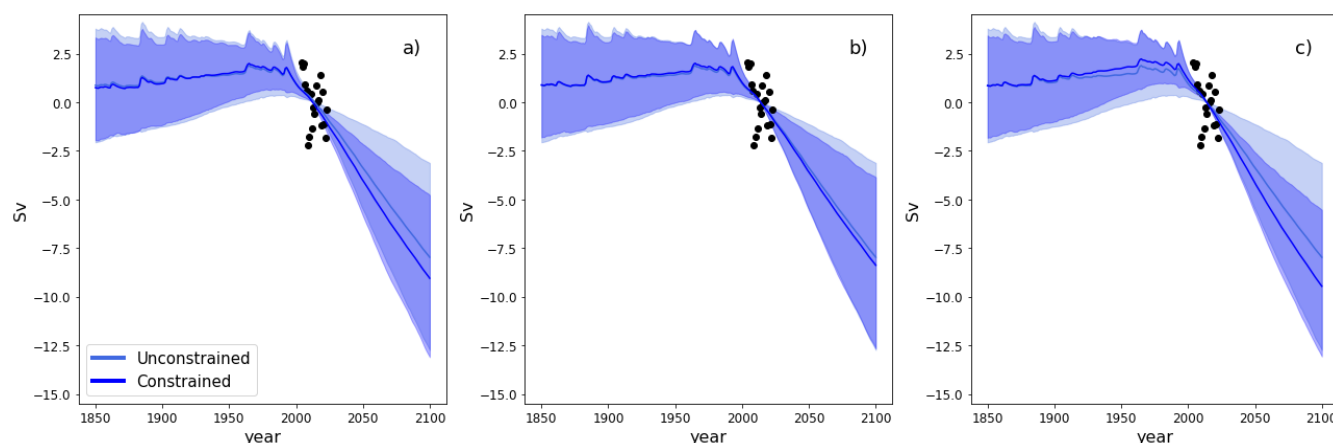


Figure 1: (a) Evolution of the (light blue) unconstrained and (blue) constrained AMOC forced response using the RAPID observational dataset and the KCC method applied to the CMIP6 multi-model ensemble. (b) Same as (a) but using the model with the maximum variance (GISS-E2-1-G) in the KCC method, (c) same as (a) but using the model with the minimum variance (NorESM2-LM) in the KCC method. The anomalies are calculated relative to the 2004–2023 period. The unconstrained and constrained ranges stand for the 5 to 95% confidence interval of the forced response as estimated from the 28 CMIP6 models. The thick line stands for the best estimate.



Using a longer observational period of 2004-2050 instead of 2004-2025 greatly improved the performance of the statistical method, with the mean of the CRPSS increasing by 10% (Figure 2). This indicates that it would be necessary to have a substantial amount of additional observations in the future to infer robust conclusions on the future AMOC changes. In addition, although a large part of the CRPSS distribution derived from the perfect model framework is positive, some members used as pseudo-observations lead to large negative CRPSS, meaning a deterioration of the accuracy in representing the forced AMOC changes in the end of the 21st century. This could be due to some members in models that are characterized by strong centennial internal climate variability (e.g. Bonnet et al. 2021), that can not be entirely captured by the sum of the AR1 processes used to estimate internal variability.

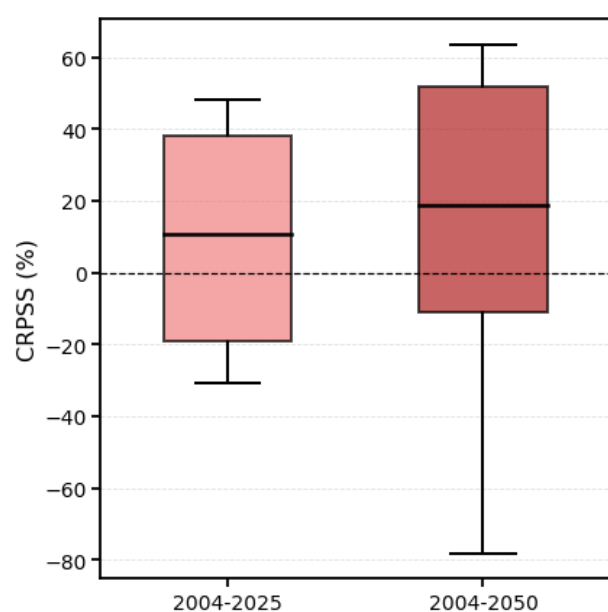


Figure 2: CRPSS calculated for the AMOC over the (light red) 2004-2025 and (dark red) 2004-2050 period using a perfect model framework alternatively considering each one of the 143 simulations (see section 2.2) as observations. The boxplots show the 5th percentile, 25th percentile, median, 75th percentile and 95th percentile.

3.2 Evaluation of the AMOC fingerprints

The results from the previous section show that constraining the forced AMOC changes using the sole observational AMOC record provides limited constraint, largely due to a non-robust estimate of internal variability, which is under-sampled in the current available observations. To alleviate this issue, we use the three SST-based AMOC fingerprints described in Section 2.2, as alternative constraints on the forced AMOC changes. The main advantage of these fingerprints is that they cover a much longer observational record.

We first quantify the tight links that exist between the AMOC and each of its assumed fingerprints. The inter-model correlation between the AMOC and three different fingerprints is evaluated for three different 50-year periods between 1900



and 2100, as well as over the end-of-century period (2081-2100) (Figure 3). When the inter-model correlation is high, the inter-model spread of the AMOC climatology is strongly related to the associated fingerprint over a given period, which suggests a potential reduction of the AMOC uncertainty within the model ensemble as an observed estimate of the fingerprint is available.

The C-index, the L-index and the I-index show similar qualitative results, with positive significant correlations for the five periods considered according to a two-sided Student's t-test ($p_value < 0.05$). These positive inter-model correlations are in line with the relationship found in previous studies between the fingerprints and the AMOC.

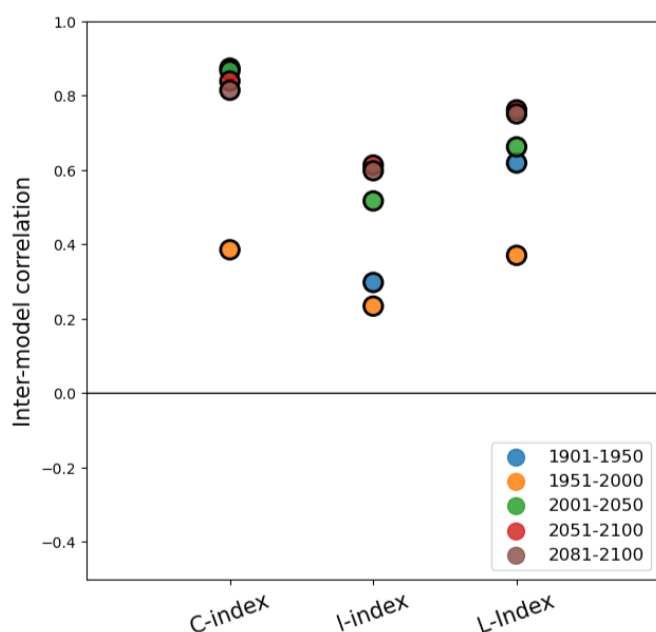


Figure 3: Inter-model Pearson correlation calculated between the AMOC anomalies and the fingerprints anomalies over 1900-1949 (in blue), 1950-1999 (orange), 2000-2049 (green), 2050-2099 (red), 1900-2024 (purple) and 2003-2024 (brown). Anomalies are calculated in each model ensemble mean (to minimize internal variability) relative to 1900-2020 for the C-index and 1961-1990 for the I-index and the L-index. For the AMOC, anomalies are calculated based on the same reference as the associated fingerprint.

The lowest correlation for the three fingerprints is found over the 1951-2000 period. Several reasons can explain these lower correlations: (i) an influence of the internal climate variability and/or the aerosol forcing can influence the AMOC fingerprints and differ among models; (ii) the relationship found between the AMOC and the fingerprints in previous model generations does not hold anymore in CMIP6. Nevertheless, the inter-model distribution of these proxies over the 21st century, which is the period of interest for this study, seems to provide information on the AMOC strength distribution over this period. Therefore, these three fingerprints seem to be potential good candidate to constrain the AMOC

3.2 Constraint of the simulated AMOC based on the different fingerprints

In this section, we estimate the constraints provided by the combination between the three AMOC fingerprints observations and the model forced response of both the fingerprints and the AMOC over 1850-2100. For the C-index and the L-index, the constrained distributions of their forced responses are reduced in variance, with the lower range ruled out over the 1850-1950 period (Figure 4a, c). For the I-index, the upper range of the uncertainty is ruled out over this period (Figure 4ab). For the next decades, the lower range of uncertainty is ruled out for the three AMOC fingerprints, as well as a smaller part of the upper range. This is associated with an upward revision of the mean forced change in comparison to the unconstrained ensembles.

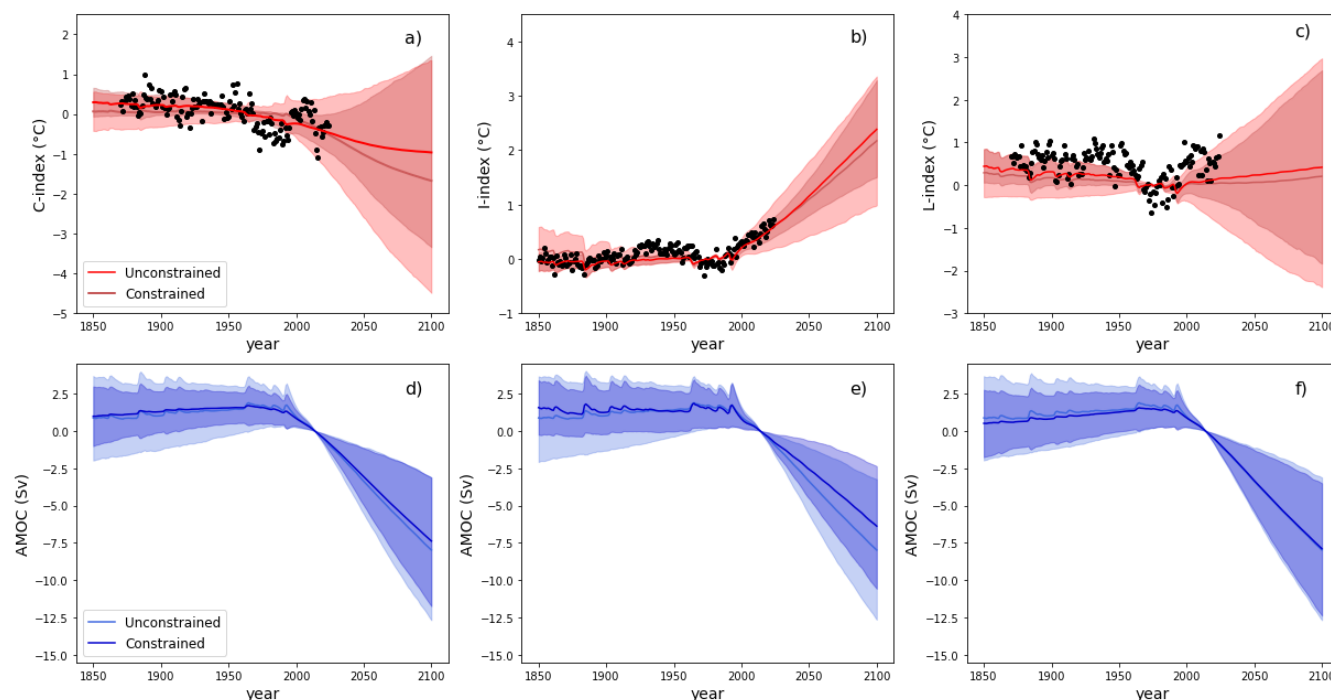


Figure 4: Evolution of the unconstrained (light red) and constrained (red) forced responses of a) the C-index, b) the I-index, and c) the L-index, based on the HadISST observational dataset and the KCC method applied to the CMIP6 multi-model ensemble. Panels d–f show the corresponding unconstrained (light blue) and constrained (blue) AMOC forced responses inferred from the C-index (d), I-index (e), and L-index (f) fingerprints. Anomalies are calculated relative to 1900–2020 for the (a) C-index, 1961–1990 for the (b-c) I-index and L-index, and 1850–1900 for the (d, e, f) AMOC. The unconstrained and constrained ranges stand for the 5 to 95% confidence interval of the forced response as estimated from the 28 CMIP6 models. The thick line stands for the best estimate.

The unconstrained AMOC forced response is about -2.9 [-0.02 ; -5.6] Sv over the near-term future (2031-2040), -4.4 [-1.0 ; -7.5] Sv over the mid-term period (2041-2060) and of -8.1 [-3.0; -12.5] Sv over the end-of-century (2081-2100) with respect to the mean AMOC strength of 17.7 Sv over the 1850-1900 period (Table 1).

Large differences are found in the constrained AMOC forced response evolution depending on the index used (Figure 4, 5). The constraint based on the C-index rules out the upper range of the uncertainties from 1850 to the beginning of the 21st



century, and then both the upper and lower range of uncertainties (Figure 4a). Hence, the models showing the weakest and largest changes of future AMOC are not compatible with the observations. Based on this fingerprint, the new estimates of the AMOC changes are of -3 [-1.1 ; -4.7] Sv over the near-term future (2031-2040), -4.3 [-2.0 ; -6.5] Sv over the mid-term period (2041-2060) and of -7.7 [-3.9 ; -11.6] Sv over the end-of-century (2081-2100) (Table 1, Figure 5b) relative to the 1850-1900 period.

The constraint based on the L-index provides a similar but much weaker constraint compared to the C-index (Figure 4d, f and Figure 5b). AMOC changes of -2.6 [-0.3 ; -4.7] Sv are obtained over the near-term future (2031-2040), -4.0 [-1.3 ; -6.7] Sv over the mid-term period (2041-2060) and of -7.7 [-3.6 ; -12.1] Sv over the end-of-century (2081-2100) with respect to the mean AMOC strength of 17.7 Sv over the 1850-1900 period (Figure 5b, Table 1).

On the other hand, the constraint based on the I-index rules out the upper range of the uncertainties up to the middle of the 21st century, similarly to the C-index. During the second half of the 21st century only the lower range of the uncertainties is revised (Figure 4e). This leads to AMOC changes of -2.9 [-0.7 ; -5.0] Sv over the near-term future (2031-2040), -4.0 [-1.3 ; -6.7] Sv over the mid-term period (2041-2060) and of -7.7 [-2.8 ; -11.3] Sv over the end-of-century (2081-2100) (Figure 5b, Table 1).

Interestingly, observations of the C-index and I-index lead to a reduction in the upper part of the uncertainty, mainly over the second part of the 20th century (Figure 4d, e). This is in line with Menary et al. (2020), who show a larger amplitude of the AMOC over the same period in the CMIP6 ensemble compared to CMIP5, in result of a stronger anthropogenic aerosol forcing on average in CMIP6. Their use of emergent constraints suggest that the anthropogenic forcing or the AMOC response may be overestimated in CMIP6 models.

Using the internal variability based on observations of the AMOC (Figure 1a) in the constraint procedure to provide future AMOC changes, we obtain anomalies of -2.4 [-0.3 ; -2.7] Sv over the near-term future (2031-2040), -4.0 [-2.1 ; -5.9] Sv over the mid-term period (2041-2060) and of -8.1 [-4.3 ; -11.7] Sv over the end-of-century (2081-2100) with respect to the mean AMOC strength of 16.2 Sv over the 2004-2023 period (Table 1; Figure 5a). The three AMOC fingerprints provide different results, with a rather weak constraint for both C-index and L-index and an opposite constraint with the I-index, rolling out simulations at the lower range of the uncertainties, leading to an AMOC change of -1.5 [-0.3 ; -2.7] Sv over the near-term future (2031-2040), -2.6 [-0.6 ; -4.5] Sv over the mid-term period (2041-2060) and of -5.6 [-2.0 ; -9.4] Sv over the end-of-century (2081-2100) (Table 1; Figure 5a).

Our different projections from the constraints indicate that it is difficult to draw any definitive conclusions, mainly because of the uncertainty associated with the internal variability of the AMOC undersampled in the observations. In addition, although the fingerprints provide longer records, they do not necessarily bring an added value since (i) they are subject to measurement errors, (ii) they do not capture the full range of physical mechanisms that drive the AMOC variability by construction. These results suggest that the current observations available can not be used to infer a robust estimate of the future trajectory of the AMOC compared to what is provided by the unconstrained uninitialised projections from CMIP6.

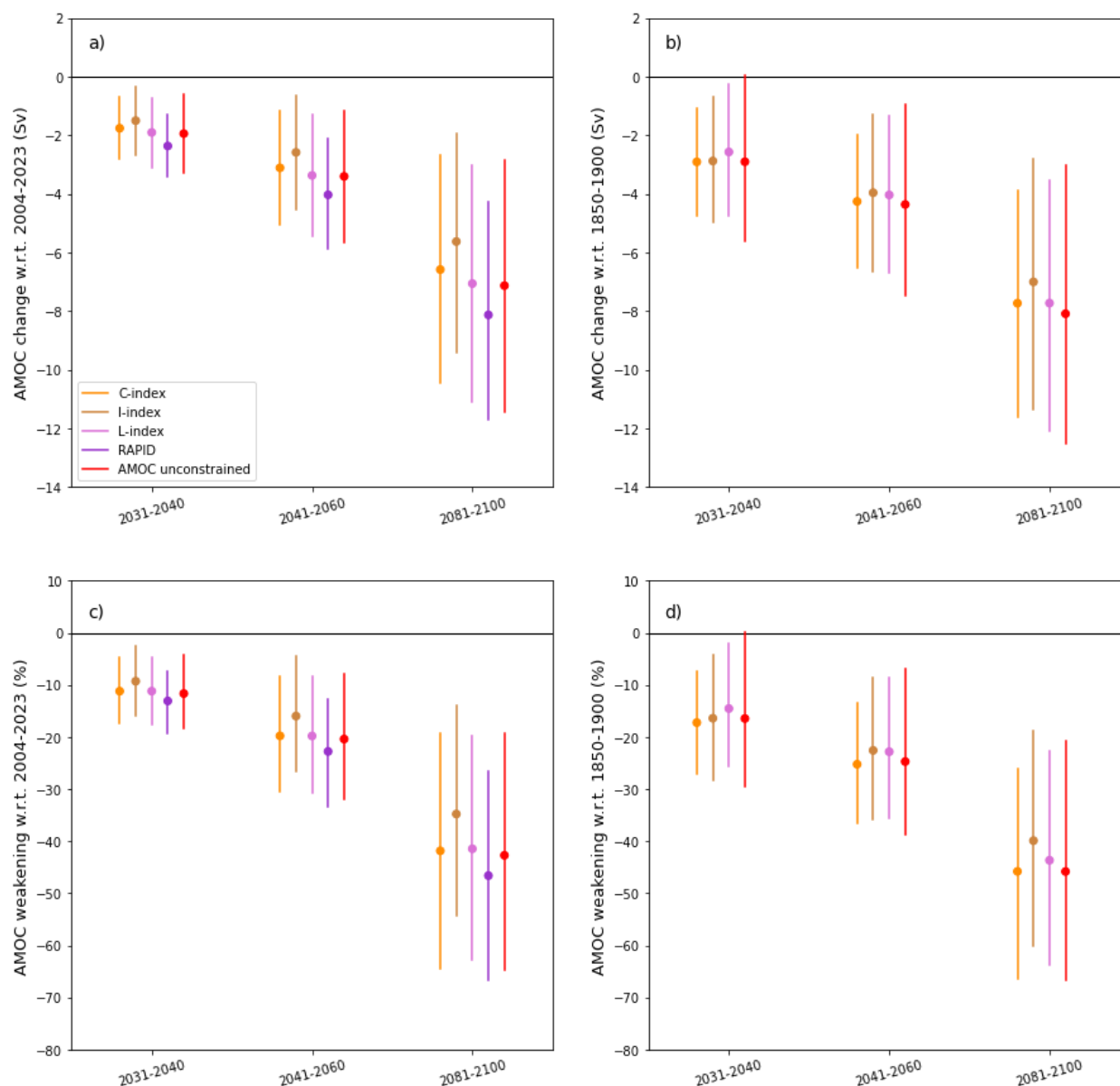


Figure 5: Change of the forced AMOC response from the KCC observational constraint method applied to the CMIP6 multi-model ensemble for four time horizons (2021-2040, 2041-2060, 2061-2080 and 2081-2100) relative to the a) 1900-1930 period and b) 2001-2021 period for the (yellow) C-index, (orange) Z-index, (brown) I-index, (pink) L-index, (purple) RAPID index and (red) for the unconstrained AMOC. The dots represent the ensemble mean and the error bars the 5-95% range. The scenario SSP5-8.5 is used from 2015 to 2100.

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AMOC change relative to 1850-1900 (Sv)			
	2031-2040	2041-2060	2081-2100
Unconstrained	-2.9 [0.02 ; -5.6]	-4.4 [-1.0 ; -7.5]	-8.1 [-3.0 ; -12.5]
C-index	-3.0 [-1.1 ; -4.7]	-4.3 [-2.0 ; -6.5]	-7.7 [-3.9 ; -11.6]
I-index	-2.9 [-0.7 ; -5.0]	-4.0 [-1.3 ; -6.7]	-7.0 [-2.8 ; -11.3]
L-index	-2.6 [-0.3 ; -4.7]	-4.0 [-1.3 ; -6.7]	-7.7 [-3.6 ; -12.1]
AMOC weakening relative to 1850-1900 (%)			
	2031-2040	2041-2060	2081-2100
Unconstrained	-16.4 [0.02 ; -29.4]	-24.7 [-6.8 ; -38.7]	-45.8 [-20.9 ; -66.7]
C-index	-17.2 [-7.4 ; -27.2]	-25.2 [-13.6 ; -36.5]	-45.8 [-26.1 ; -66.5]
I-index	-16.4 [-4.2 ; -28.2]	-22.6 [-8.7 ; -35.9]	-39.9 [-18.8 ; -60.2]
L-index	-14.5 [-2.0 ; -25.6]	-22.8 [-8.7 ; -35.5]	-43.7 [-22.7 ; -63.7]
AMOC change relative to 2004-2023 (Sv)			
	2031-2040	2041-2060	2081-2100
Unconstrained	-1.9 [-0.6 ; -3.4]	-3.4 [-1.2 ; -5.7]	-7.1 [-2.9 ; -11.4]
Observed AMOC	-2.4 [-1.3 ; -3.4]	-4 [-2.1 ; -5.9]	-8.1 [-4.3 ; -11.7]
C-index	-1.8 [-0.7 ; -2.8]	-3.1 [-1.2 ; -5]	-6.6 [-2.7 ; -10.4]
I-index	-1.5 [-0.3 ; -2.7]	-2.6 [-0.6 ; -4.5]	-5.6 [-2 ; -9.4]
L-index	-1.9 [-0.7 ; -3.1]	-3.4 [-1.3 ; -5.4]	-7 [-3 ; -11.1]
AMOC change relative to 2004-2023 (Sv)			
	2031-2040	2041-2060	2081-2100
Unconstrained	-11.7 [-4.2 ; -18.4]	-20.4 [-8 ; 31.9]	-42.7 [-19.4 ; -64.8]
Observed AMOC	-13.1 [-7.3 ; -19.2]	-22.8 [-12.7 ; -33.3]	-46.6 [-26.5 ; -66.6]
C-index	-11.2 [-4.8 ; -17.4]	-19.8 [-8.4 ; -30.6]	-41.8 [-19.3 ; -64.6]
I-index	-9.3 [-2.5 ; -15.8]	-16 [-4.6 ; -26.5]	-34.8 [-13.8 ; -54.3]
L-index	-11.2 [-4.6 ; -17.5]	-19.8 [-8.5 ; -30.8]	-41.4 [-19.8 ; -62.9]

290 **Table 1: AMOC changes relative to the 1850-1900 period in (Sv) and (%) for the near-term future (2031-2040), the mid-term future (2041-2060) and the end of the 21st century (2081-2100) for the unconstrained and the constrained ensembles. Interval confidences in brackets are from 5-95 quantiles of the distributions.**

4. Discussion and Conclusions

295 In this study, we estimate the capacity of several AMOC fingerprints as well as of the available AMOC observations to constrain the uncertainties associated with the AMOC decline in the CMIP6 multimodel projections. Using the observed AMOC results in a larger AMOC weakening of about -46.6% [-26.5; -66.7] in comparison to the unconstrained AMOC change of -42.7% [-19.4; -64.8], reducing the uncertainty range by 11.5%. However, this result is however very sensitive to the internal variability (Figure 1), and we show that longer observations may provide a better constraint (Figure 2). It highlights that the available AMOC observations from RAPID are not yet available over a long enough period to provide a robust estimate of its internal variability which would allow a better estimate of the associated forced response. This



300 therefore suggests that results from previous studies constraining AMOC changes based on the observed AMOC should be taken with caution.

Very different results are also found using various AMOC fingerprints. While the L-index and the C-index provides only a limited constraint on the AMOC forced change over the 21st century, the I-index provides an opposite constraint than the one from the observed AMOC, of about -38.8% [-13.8; -54.3] for the end of the century, ruling out the lower range of the simulations with respect to the 2004-2023 reference period.

When considering the AMOC weakening over the end of the 21st century (2081-2100) relative to the 1850-1900 reference period, differences are also found between the indexes used to constrain the AMOC forced changes. The C-index is mainly rolling out the upper range of simulations, with relative AMOC changes of about -45.8 [-20.9 ; -66.7] % , whereas the I-index is rolling out mainly the lower range of the simulations, with AMOC changes of about -39.9 [-18.8 ; -60.2] %.

310 These differences can be explained by several reasons. First, the physical mechanisms explaining the link between the inter-model spread of fingerprints and the AMOC inter-model spread may differ depending on the different generations of models compared to the reference papers which have used these fingerprints. However, we still find that the correlations provide a positive significant relationship, suggesting that it still holds for the current CMIP6 models. These AMOC fingerprints can also be influenced by other factors than the AMOC, over the historical period and therefore could provide blurry information to constrain the AMOC. For example, several studies highlight that the warming hole over the North Atlantic subpolar gyre could be a response to change in the atmospheric circulation rather than the AMOC (He et al., 2022; Kramer et al., 2024). These differences therefore highlight the difficulty of constraining the AMOC considering the limited length of the observational record or the use of AMOC fingerprints.

320 The use of other fingerprints, based on salinity or ocean heat content (e.g. Zhang et al., 2008, 2017 ; Zhu and Liu, 2020) would be relevant. This is however difficult because of the limited availability of these variables in CMIP6 models, from which we cannot provide a robust estimate of the model uncertainty. This argues for more models to include key variables related to salinity in order to understand the AMOC variability.

Although differences are found in the forced AMOC response over the 21st century, none of the constraints used suggest a potential AMOC collapse before the end of the 21st century (i.e. 80% AMOC weakening, IPCC SROCC Chap 6). Nevertheless, a substantial weakening (i.e. 50% AMOC weakening, IPCC SROCC Chap 6) is to be considered before the end of the century, leading to strong impact (e.g. Bellomo et al., 2021; 2023).

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Data statement. All CMIP6 data are available through the Earth System Grid Federation. The HadISST dataset (Rayner et al., 2003) is publicly available for download at <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. The HadCRUT5 dataset (Morice et al. 2021) is publicly available for download from the C3S store: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download>. The RAPID AMOC dataset is publicly available for download at <https://rapid.ac.uk/data/> (last access: February 2026).

Author contributions. RB and SQ designed the study. RB processed the data, performed the calculations of the indices and the analyses. SQ performed the KCC method. RB prepared the paper with contributions from SQ.

Competing interest. The authors declare no competing of interest.

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